Building Research Journal

A Journal of Applied Research

Volume 3, Number 1
Spring 1994

National Consortium
of Housing Research Centers

Building Research Journal

Volume 3 | 1994 | Number 1

Co-Editors Matt Syal
Jack H. Willenbrock

Managing Editor Lisa A. Busjahn
Copy Editor Julia A. Goldberg

Graphic Designer Selah D. Peterson
Cover Design Michelle R. Dressen

The *Building Research Journal* is a publication of the School of Architecture-Building Research Council, College of Fine & Applied Arts, University of Illinois at Urbana-Champaign. The *Building Research Journal* provides a forum for technical research of interest to a wide range of building-related disciplines. Subscriptions and inquiries should be sent to *Building Research Journal*, School of Architecture-BRC, One East St. Mary's Rd., Champaign, IL 61820-6995 (phone: 217 333-1801). The *Journal* is published semi-annually, one volume per year. The annual subscription rate is $30.00 for individuals and $80.00 for institutions.

Made in the United States of America.

ISSN 92-002353

ORDER FORM

Name ______________________________

Street Address ______________________________

City ______________ State __________ Zip __________

Phone (______) __________ Fax (______) __________

SEND ORDERS TO:
School of Architecture–Building Research Council
College of Fine and Applied Arts
University of Illinois at Urbana-Champaign
One East St. Mary's Road
Champaign, IL 61820

CALL: (800) 336-0616 FAX: (217) 244-2204

	DOMESTIC	INT'L
❑ One year personal subscription to the *Building Research Journal*	$30.00	$36.00
❑ One year institutional subscription to the *Building Research Journal*	$80.00	$96.00

❑ VISA ❑ MasterCard

Acct #: ________-________-________-________

Exp. Date: ______________________________

Cardholder's Signature: ______________________________

Make your check or money order payable to the University of Illinois. On purchase orders, use your Federal Employers Identification Number.

ORDER FORM

Name ______________________________

Street Address ______________________________

City ______________ State __________ Zip __________

Phone (______) __________ Fax (______) __________

SEND ORDERS TO:
School of Architecture–Building Research Council
College of Fine and Applied Arts
University of Illinois at Urbana-Champaign
One East St. Mary's Road
Champaign, IL 61820

CALL: (800) 336-0616 FAX: (217) 244-2204

	DOMESTIC	INT'L
❑ One year personal subscription to the *Building Research Journal*	$30.00	$36.00
❑ One year institutional subscription to the *Building Research Journal*	$80.00	$96.00

❑ VISA ❑ MasterCard

Acct #: ________-________-________-________

Exp. Date: ______________________________

Cardholder's Signature: ______________________________

Make your check or money order payable to the University of Illinois. On purchase orders, use your Federal Employers Identification Number.

Table of Contents

Reviewer List

In addition to the members of the editorial board, the following people have reviewed papers submitted to this issue of the *Building Research Journal.*

Phyllis Adams-Barner
Housing Research Center
The Pennsylvania State University

Ed Barbour
Research Division
NAHB Research Center

Paul Fisette
Building Materials Technology and Management
University of Massachuetts - Amherst

Timothy Larson
Department of Forest Products
University of Minnesota - St. Paul

James D. Lutz
College of Engineering
Auburn University

Mark Nowak
Research Division
NAHB Research Center

Neil Opfer
Construction Management & Programming
University of Nevada at Las Vegas

Michael C. Osborne
Indoor Air Branch (MD-54)
United States Environmental Protection Agency

J.T. Pearson
School of Mechanical Engineering
Purdue University

T. Agami Reddy
Department of Mechanical Engineering
Texas A&M

March 1994

Dear Readers:

This issue marks the third year of publication for the *Building Research Journal*. It represents the technology transfer mission of the Building Research Council of the University of Illinois at Urbana-Champaign and the National Consortium of the Housing Research Centers.

This journal has gone through a remarkable maturing and refinement process over the last four issues. During this time, we have broadened the scope to include Infrastructure Planning and Development topics. With the Fall 1993 issue, we started a new feature section titled: "News, Updates, and Seminars." This section was originally designed to provide the opportunity to share and discuss ideas and events in an informal format. With the current issue, we have expanded the "News, Updates, and Seminars" section to include selected activities of the members of the National Consortium of the Housing Research Centers.

In past issues, we have tried to balance the papers so that they represent several emphasis areas of the journal. In this issue, we have deviated from the practice and decided to focus on one area. The four papers in this issue represent the area of "Building Design, Operation, and Performance." We would like to receive your comments in this regard.

The paper by G. K. Yuill and E. D. Werling deals with the calculation of residential heating energy requirements. The analysis of one of the main causes of indoor air quality problems and its spread through the HVAC system is presented in the paper by Ossama A. Abdou and Francis A. Sando. Ardeshir Mahdavi and Khee Poh Lam discuss building performance simulation in their paper. The final paper by Elizabeth Kossecka, Jan Kosney, and Jeffrey E. Christian presents a mathematical model for estimating thermal resistance of a wall.

We would like to thank the contributors, the reviewers, the Building Research Council staff and the members of the Editorial Board for their input. We would also like to thank the readers for making this publication a success. Your submissions, subscriptions, comments and suggestions are welcome.

Matt Syal

Matt Syal, Co-editor
Assistant Professor
Construction Management
Colorado State University

Jack H. Willenbrock

Jack H. Willenbrock, Co-editor
Bernard and Henrietta Hankin Chair of
Residential Building Construction
The Pennsylvania State University

CALL FOR PAPERS

Building Research Journal

The *Building Research Journal* publishes refereed articles focusing on interdisciplinary building research. The *Journal* seeks the submission of articles related to building technology, automation, materials, design, construction, performance, and operations. Articles are reviewed and must meet the highest standards of research, scholarship, and technical merit.

PUBLISHER

School of Architecture—Building Research Council
College of Fine and Applied Arts
University of Illinois at Urbana-Champaign
One East St. Mary's Road
Champaign, Illinois 61820
Contact: Lisa Busjahn (217) 333-1801 FAX: (217) 244-2204

ORGANIZATION OF THE JOURNAL

The operations are directed by an editorial board, composed of members of the National Housing Research Centers Consortium and other eminent researchers from universities, government, and industry.

DESCRIPTION OF THE JOURNAL

The *Journal* publishes six to eight major articles per issue. Authors' guides are available upon request. Future issues will feature a section devoted to short descriptions of research in progress to foster communication among researchers.

PUBLICATION SCHEDULE

The semi-annual publication cycle is timed to coincide with university academic semesters. Submissions to the *Journal* are welcome throughout the year.

SUBMISSION INFORMATION

For more information regarding the submission of research papers to the *Journal*, contact:

Jack H. Willenbrock
Co-Editor
Penn State University
(814) 863-0623

Matt G. Syal
Co-Editor
Colorado State University
(303) 491-5805

Lisa A. Busjahn
Managing Editor
Building Research Council
(217) 333-1801

Encourage your library and department to subscribe to the *Building Research Journal.*

Interpolating Residential Heating Energy Requirements

G. K. Yuill and E. D. Werling

ABSTRACT

Life cycle cost optimization of residential heating equipment requires knowledge of annual heating energy requirements. Traditionally, the degree-day method has been used. More accurate methods, using computer simulation, are available, but they require hourly weather data which is not available at many locations. This problem could be solved by interpolation between the nearest sites with available hourly weather data.

BLAST was used to calculate heating energy requirements for three houses at 34 sites in the northeastern United States with available hourly weather data. Then, 24 of the 34 sites were used to evaluate the accuracy of various prediction methods, including the degree-day method, distance weighting factors, and linear and non-linear interpolation. Ten boundary sites were needed for interpolation at sites near the boundaries of the region considered.

The accuracy of the degree-day method was worse than any of the other methods. Standard errors of four to seven percent were observed for the better interpolation methods, compared with over 11 percent for the degree-day method. The best interpolation methods allow the analyst to predict residential heating energy requirements at a site for which weather data are not available, without introducing significant error.

Dr. G.K. Yuill is a Professor of Architectural Engineering at The Pennsylvania State University.

E.D. Werling is completing a Master of Science in Architectural Engineering at The Pennsylvania State University.

INTRODUCTION

Life cycle cost optimization of residential heating equipment requires a knowledge of annual heating energy requirements for the house of interest, local utility rates, and the costs of equipment components being considered. Utility rates and equipment costs are not difficult to determine. However, annual heating energy requirements, which depend on house characteristics, occupant behavior, and local weather, can be more difficult.

Traditionally, the degree-day method has been used to estimate heating energy requirements. However, it is not accurate, and is becoming less accurate as houses become more energy conserving and appliance energy use increases. More accurate methods, using computer simulation of building energy use, are available, but they require hourly weather data, which is not available at many locations. This problem could be solved by interpolation, using simulated heating energy requirements at the nearest sites for which hourly weather data are available. This paper presents several such methods for estimating annual heating energy requirements, and compares the accuracy of each.

GENERAL APPROACH

In this project, the BLAST computer program (Building Loads Analysis and System Thermodynamics, U.S. Army CERL)(BLAST 1991) was used to calculate the annual heating energy requirements for three house designs at 34 sites in the northeastern United States for which the required weather data were available **(Figure 1)(Table 1)**. Then, 24 of the 34 sites (all but the boundary sites) were selected as

Table 1: BLAST Reference Locations

City	Elevation	Latitude	Longitude
Hartford, CT	19ft	41.7	72.7
Wilmington, DE	74ft	39.7	75.6
Washington, D.C.	14ft	38.9	77.0
Caribou, ME*	624ft	46.9	68.0
Portland, ME	43ft	43.7	70.2
Baltimore, MD	148ft	39.2	76.7
Patuxent River, MD*	50ft	38.3	76.2
Boston, MA	15ft	42.4	71.0
Concord, NH	342ft	43.2	71.5
Lakehurst, NJ*	20ft	39.9	74.1
Newark, NJ	7ft	40.7	74.2
Albany, NY	275ft	42.8	73.8
Binghamton, NY	1590ft	42.2	76.0
Buffalo, NY*	705ft	42.9	78.7
Massena/Richards, NY*	207ft	44.9	74.9
New York, NY	13ft	40.7	73.8
Rochester, NY	547ft	43.1	77.7
Syracuse, NY	410ft	43.1	76.1
Akron, OH	1208ft	40.9	81.4
Cincinnati, OH*	758ft	39.2	84.5
Cleveland, OH	777ft	41.4	81.9
Columbus, OH	812ft	40.0	82.9
Dayton, OH*	1002ft	39.9	84.2
Toledo, OH*	669ft	41.6	83.8
Youngstown, OH	1178ft	41.3	80.7
Allentown, PA	387ft	40.7	75.4
Erie, PA	731ft	42.1	80.2
Harrisburg, PA	308ft	40.2	76.8
Philadelphia, PA	5ft	39.9	75.3
Pittsburgh, PA	1137ft	40.5	80.0
Scranton, PA	930ft	41.3	75.7
Providence, RI*	51ft	41.7	71.4
Burlington, VT	332ft	44.5	73.2
Charleston, WV*	939ft	38.4	81.6

*Boundary site source: ASHRAE Fundamentals, 1993

Figure 1. Weather Data Locations

test sites to evaluate the accuracy of the various prediction methods. The accuracy of each method was quantified by comparing the prediction method estimates with the BLAST simulations at the same 24 sites. The ten boundary sites were needed to interpolate heating energy requirements at sites near the boundaries, but they themselves could not be used for interpolation, since they were at the edges of the region considered. For example, simulations of Ohio and West Virginia sites were needed to interpolate heating energy requirements in western Pennsylvania locations.

The compared prediction methods included:

- the degree-day method;
- weighting computed estimates at the nearest three sites by inverse distances;
- weighting computed estimates at the nearest three sites by inverse square distances;
- linear interpolation;
- second-order interpolation;
- inverse square distance weighting with a linear correction for elevation;
- linear interpolation with a linear correction for elevation; and
- second-order interpolation with a linear correction for elevation.

BLAST simulations were used as benchmarks rather than using actual measured heating energy requirements because of the large number of locations required to evaluate the prediction methods, and because BLAST has been validated extensively (Andersson et al. 1980)(Bauman et al. 1983)(Herron et al. 1980)(Yuill 1985 and 1986)(Yuill and Phillips 1981). BLAST gives accurate results when building and weather input data are accurate.

THE BLAST SIMULATION MODEL

General Description

Three typical modular house sizes were modeled using BLAST: a 1-story 1,500 ft^2 (139 m^2) house [House 1], a 2-story 2,250 ft^2 (209 m^2) house [House 2], and a 2-story 3,000 ft^2 (279 m^2) house [House 3]. The simulation models were based on the plans for a modular house with 2,250 ft^2 (209 m^2) of finished floor area (excluding basement) built over a full basement foundation in 1992 in central Pennsylvania (the Base House). The house has standard wood frame construction, with 2x6 insulated exterior walls, insulated first floor, insulated second story ceiling, double pane low-emissivity (low-e) windows, and a vented un-insulated attic. A summary of the component areas and the overall thermal resistances is given in **Table 2**.

Each house was modeled in BLAST as three thermal zones (the living space, an unconditioned basement, and an attic) with typical schedules for occupancy, lighting, and electric appliances for their respective house size. Total annual energy consumption for lighting and appliances (excluding HVAC) was 7,000 kWH in House 2, based on data from a West Penn Power study of residential electric demand in houses of the same size (Burt, Hill, Kosar, Rittelmann Associates 1992). For Houses 1 and 3, lighting energy was scaled to floor area and appliance energy use was scaled to occupancy. BLAST simulations were run with TMY (typical meteorological year) or TRY (test reference year) weather data for each of the 34 locations in the northeastern United States.

Basement Model and Ground Temperatures

No available hourly energy analysis programs have accurate algorithms for estimation of basement heat loss, since it would not be practical to simulate three dimensional transient heat transfer on an hourly basis. Instead, BLAST calculates basement heat loss by assuming one-dimensional conductive heat transfer for the basement floor and the below-grade portion of basement walls. It also assumes a ground temperature for each month. The difficulty is to determine an effective ground temperature for each month that gives approximately the same results as a more precise, but prohibitively complex, three dimensional transient heat transfer simulation.

Mitalas' procedure for calculation of residential below grade heat loss (Mitalas 1987) was used to determine these effective monthly ground temperatures for each of the 34 locations in the BLAST simulation model. Mitalas' procedure uses Basement Heat Loss Factors for calculation of basement heat loss, based on

Table 2. House Component Areas and R-Values

Component	House 1 Total Area	House 2 Total Area	House 3 Total Area	R-Value*
Walls	1067 ft^2 (99 m^2)	1847 ft^2 (172 m^2)	2215 ft^2 (206 m^2)	19 (3.3)
1st-Floor Floor	1500 ft^2 (139 m^2)	1375 ft^2 (128 m^2)	1500 ft^2 (139 m^2)	19 (3.3)
1st-Floor Ceiling	1500 ft^2 (139 m^2)			30 (5.3)
2nd-Floor Ceiling		1375 ft^2 (128 m^2)	1500 ft^2 (139 m^2)	30 (5.3)
Windows	164 ft^2 (15.2 m^2)	264 ft^2 (24.5 m^2)	328 ft^2 (30.5 m^2)	3.125 (0.55)
2 Wood Doors	41 ft^2 (3.8 m^2)	41 ft^2 (3.8 m^2)	41 ft^2 (3.8 m^2)	7.19 (1.27)
Glass Patio Door	40 ft^2 (3.7 m^2)	40 ft^2 (3.7 m^2)	40 ft^2 (3.7 m^2)	3.45 (0.61)

* hr-ft^2-°F/Btu (m^2-°C/W)

Table 3. BLAST Infiltration Coefficients from LBL Correlated Daily Infiltration Rates

CITY	A	B	C	D
Scranton, PA	1.3255	-0.0128	0.000408	4.76 E-8
Harrisburg, PA	1.3355	-0.0127	0.000407	5.82 E-8
Washington, D.C.	1.3541	-0.0122	0.000281	1.39 E-7
Portland, ME	1.3709	-0.0129	0.000324	9.97 E-8

foundation type and geometry, basement insulation levels, local weather, indoor temperature, and soil thermal conductivity.

Infiltration

Infiltration is modeled in BLAST with a correlation of the form:

$$I = I_{max} F [A + B(T_i - T_o) + Cv + Dv^2] \quad (1)$$

where,

I = estimated infiltration rate, cfm (L/s);

I_{max} = user-specified maximum infiltration rate, cfm (L/s);

F = user-specified fractional infiltration schedule, dimensionless (1 for this study);

T_i = average indoor temperature for the hour (thermostat setting), °F (°C);

T_o = average ambient outdoor temperature for the hour, °F (°C);

v = average wind speed for the hour, ft/min (m/s);

A-D= user-specified coefficients.

While this model offers user flexibility in specifying infiltration rates, it is not based on physical reality. A more accurate infiltration model, based on the Lawrence Berkeley Laboratory (LBL) model (ASHRAE 1993)(Sherman 1986) takes the form:

$$I = L\sqrt{A\,(T_i - T_o) + Bv^2} \quad (2)$$

where,

L= measured Effective Leakage Area (ELA), in.^{2} (cm^2);

v = average wind speed for the hour, mph (m/s);

A = stack coefficient, cfm^2/in.^{4}°F {(L/s)^2/cm^4°C} [0.0156 (0.000145) for House 1, and 0.0313 (0.000290) for Houses 2 & 3];

B = wind coefficient, cfm^2/in.^{4}mph^2 {(L/s)^2/cm^4(m/s)^2} [0.0039 (0.000104) for House 1, and 0.0051 (0.000137) for Houses 2 & 3].

To accurately model infiltration for this study the ELA of the Base House was measured using a blower door (CGSB 1986), and the average infiltration rate was calculated for each day of the year using the LBL model. Weather data for Scranton, PA, which most closely matched the climate at the site of the house tested in central Pennsylvania, were used in the calculations. The daily averaged infiltration rates were then correlated to an equation of the same form as the BLAST infiltration model, to solve for the BLAST infiltration model coefficients, A-D **(Table 3, Scranton)**. The correlation was excellent, especially at high infiltration rates, indicating that the BLAST infiltration model, with these correlation coefficients, accurately calculated LBL model infiltration rates.

To check the validity of the Scranton coefficients at other sites, the procedure was repeated for three additional locations. The new coefficients **(Table 3)** were used to estimate infiltration in the Scranton house and compared with the original set. The correlations for all

three cases were excellent (standard errors of less than 1 cfm), showing that the coefficients developed using Scranton weather could be applied at any location.

BLAST Simulations

Energy analysis results from the BLAST simulations are shown in **Table 4**. Annual heating energy requirements varied from 14,600,000 BTU (4,280 kWH) for House 1 in Patuxent River, Maryland to 67,000,000 BTU (19,600 kWH) for House 3 in Caribou, Maine. Winter design heat loss was calculated by defining a BLAST temporary design day, using the ASHRAE design conditions (ASHRAE 1989) and ignoring solar and internal gains. Design heat loss ranged from 13,500 Btu/Hr (3.96 kW) for House 1 in Washington, D.C. to 33,600 Btu/Hr (9.85 kW) for House 3 in Caribou, Maine.

PREDICTION METHODS

Degree-day Method

The degree-day method is a simplified heating energy consumption estimation procedure (ASHRAE 1989) based on the assumption that heating energy consumption varies linearly with the difference between the mean daily outdoor temperature and a base temperature. This base temperature is the temperature at which solar and internal gains to the house exactly offset the overall heat loss through the house envelope by conduction, infiltration and ventilation, and is assumed to be 65°F. Considering seasonal equipment efficiency, the degree day method can be used to estimate heating energy consumption. By ignoring equipment efficiency, the degree-day equation used to estimate the annual heating energy requirement is:

$$E = C_D \frac{24 q_L DD}{\Delta T} \tag{3}$$

where,

E = estimated annual heating energy requirement, BTU;

q_L = design heat loss, including infiltration, BTU/Hr;

DD = number of 65°F degree-days per year;

ΔT = winter design temperature difference ($T_{indoor} - T_{design}$), °F;

C_D = empirical correction factor for heating effect versus 65°F degree-days.

The degree-day method is easy to use and degree-days data are available for many locations in the U.S. and Canada. However, the method is based on the design heat loss for the house which does not directly account for solar and internal gains, or transient heat transfer, and relies on a simplified estimate of infiltration losses. These simplifying assumptions can result in large errors (Claridge et al. 1987)(Fischer et al. 1982).

Variations in building materials, thermostat settings, and appliance energy consumption affect the base temperature, and thus the accuracy of the degree-day method. The use of variable base degree-days (ASHRAE 1993) to determine the actual base temperature (usually below 65°F) for a house would improve the accuracy of the degree-day method. However, this would require the use of more detailed weather data. With detailed weather data available, more accurate simulation methods would be preferred. The question remains, which method to use when detailed weather data are not available?

Inverse Distance Weighting Factor

Weighting factor methods were used to estimate the annual heating energy requirement for a house in a given location, by using simulated annual heating energy requirements for the same house in three locations where hourly weather data were available. The estimate was made by weighting the "known" heating energy requirements by the inverse of the distance between the chosen location and the reference locations. The reference locations chosen were the nearest sites with available weather data, so that they formed a triangle around the location of interest **(Figure 2)**. This method gives nearer locations greater weight, and results in a straight numerical average if all three locations are equidistant from the location of interest.

Table 4. BLAST Simulated Annual Heating Energy Requirements and Winter Design Loads

CITY	House 1 Annual (MMBtu)	House 1 Design (kBtu/H)	House 2 Annual (MMBtu)	House 2 Design (kBtu/H)	House 3 Annual (MMBtu)	House 3 Design (kBtu/H)
Hartford, CT	25.4	14.6	35.7	21.0	42.7	25.5
Wilmington, DE	19.0	14.3	27.1	20.9	32.4	25.6
Washington, D.C.	17.1	13.5	24.7	19.8	29.3	24.3
Caribou, ME	40.4	19.7	55.9	27.7	67.0	33.6
Portland, ME	30.4	16.5	42.5	23.6	50.8	28.6
Baltimore, MD	18.4	14.3	26.5	20.8	31.7	25.4
Patuxent River, MD	14.6	14.2	18.4	19.6	21.9	24.1
Boston, MA	25.1	16.5	35.8	24.0	43.2	29.6
Concord, NH	29.7	16.9	41.3	24.1	49.3	29.3
Lakehurst, NJ	18.2	13.9	26.0	20.3	31.0	24.8
Newark, NJ	19.2	14.3	27.3	20.9	32.8	25.6
Albany, NY	26.7	16.8	37.3	23.9	44.6	29.1
Binghamton, NY	34.1	16.7	47.5	24.0	56.8	29.2
Buffalo, NY	32.2	15.7	45.4	22.7	54.7	27.7
Massena/Richards, NY	35.3	18.6	48.7	26.4	58.4	32.1
New York, NY	20.6	14.8	29.5	21.7	35.4	26.7
Rochester, NY	32.9	15.7	46.3	22.8	55.7	27.9
Syracuse, NY	31.5	16.3	44.3	23.2	53.1	28.3
Akron, OH	26.6	15.5	37.5	22.4	44.9	27.4
Cincinnati, OH	18.7	16.1	26.5	23.3	31.6	28.6
Cleveland, OH	28.5	16.2	40.0	23.4	47.8	28.6
Columbus, OH	22.6	15.4	32.0	22.1	38.3	26.9
Dayton, OH	23.2	16.6	32.8	24.0	39.3	29.3
Toledo, OH	27.6	16.1	38.8	23.1	46.5	28.1
Youngstown, OH	29.8	16.3	42.0	23.4	50.3	28.6
Allentown, PA	24.2	15.5	34.1	22.4	41.0	27.4
Erie, PA	29.5	15.1	41.7	21.9	50.1	26.8
Harrisburg, PA	20.1	15.2	28.5	22.1	34.0	27.1
Philadelphia, PA	18.9	14.4	27.0	21.1	32.3	25.9
Pittsburgh, PA	25.8	15.8	36.3	22.7	43.4	27.7
Scranton, PA	25.8	15.5	36.2	22.3	43.2	27.2
Providence, RI	24.7	14.9	34.9	21.7	41.8	26.6
Burlington, VT	32.6	17.7	45.3	24.9	54.2	30.2
Charleston, WV	16.6	14.2	24.0	20.6	28.4	25.1
min	14.6	13.5	18.4	19.6	21.9	24.1
max	40.4	19.7	55.9	27.7	67.0	33.6

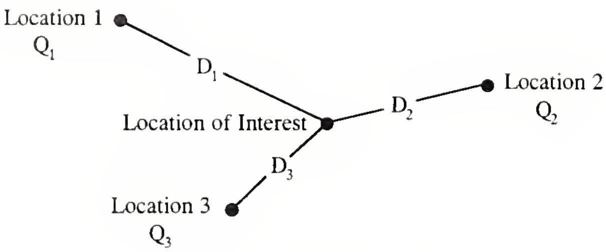


Figure 2. Weighting Factor Methods

The inverse distance weighting factor procedure used to estimate heating requirements can be represented by the following equation:

$$E = \sum_{1}^{3} \frac{Q_i}{D_i} / \sum_{1}^{3} g \frac{1}{D_i} \tag{4}$$

where,

Q_i = BLAST simulated heating energy requirement for a reference location, BTU;

D_i = distance between the location of interest and a reference location, degrees.

Since latitude and longitude were readily available for every location, the distances between the location of interest and each of the reference locations were calculated in degrees from the following equation:

$$D_i = \sqrt{(L - L_i)^2 + (\Phi - \Phi_i)^2} \tag{5}$$

where,

L_i = longitude, degrees, subscript indicating a reference location;

Φ_i = latitude, degrees.

This distance formula is not exactly correct since latitude and longitude are only equivalent at the equator. However, for ease of calculation, these errors were ignored, since all locations were subject to approximately the same error. These errors did not affect the heating requirement estimates.

The inverse distance weighting factor method was an improvement over the degree-day method because it was based on detailed computer simulations of the house in question, which accurately considered the effects of solar and internal gains, heat storage (thermal transients), and infiltration losses. However, the method did not account for differences in climate not explainable by latitude and longitude differences, such as the effects of elevation, proximity to large bodies of water, etc.

Inverse Square Distance Weighting Factor

The inverse square distance method used was the same basic procedure as the inverse distance method. The difference was the method placed greater weight on the nearest reference locations by squaring the distances in the weighting factor. The estimates were calculated with the following equation:

$$E = \sum_{1}^{3} \frac{Q_i}{D_i^2} / \sum_{1}^{3} \frac{1}{D_i^2} \tag{6}$$

This method offered a slight improvement over the inverse distance method because it gave extra weight to the nearer locations.

Linear Interpolation

This method was similar to the weighting factor technique since the heating energy requirement estimate was based on known heating energy requirement values from nearby locations. However, instead of weighting by distance alone, a linear relationship was assumed between geographical location and annual heating energy requirements. That is, heating energy requirement was assumed to be directly related to latitude and longitude. Based on this assumption, an equation for heating energy requirement was developed using the known values from nearby reference locations, from which the house annual heating energy requirement in the location of interest was estimated. The equation was of the form:

$$E = aL + b\Phi + c \tag{7}$$

where the coefficients a, b, and c were determined by solving the equation simultaneously with the data points from the reference locations. With three data points (locations with known annual heating energy requirements) an exact solution to this system of three linear equations, was found using algebraic methods. When more data points were used, it became a

simple multiple linear regression and was solved by the method of least squares.

Second-Order Interpolation

This method was based on the same principle as the linear interpolation method, except that a higher order relationship (non-linear) was assumed between location and annual heating energy requirements. The relationship took the form:

$$E = aL + b\Phi + cL\Phi + dL^2 + e\Phi^2 + f \quad (8)$$

This method required data from six or more locations to solve for the six coefficients.

Number of Weather Data Locations

The number of weather data locations used in the linear and second order interpolation methods was varied to determine its effect on the accuracy of the interpolations. It was expected that increasing the number of locations would improve the statistical accuracy of each method. The minimum sample size that gives a good prediction would be desirable for most circumstances. The base case for each interpolation method was the minimum number of locations required to get a solution (i.e. three for linear and six for 2nd order interpolation). The largest number of locations used was 24, the number of locations with verifiable BLAST simulations. In these large sample correlations, three separate correlations were performed (24 sample points each) for the three different house sizes.

Elevation Correction

An effort was made to improve the accuracy of the weighting factor and interpolation methods by considering elevation in the correlations. It was hypothesized that most of the unbiased variation in annual heating energy requirements not explainable by latitude and longitude can be accounted for by elevation. The elevation correction for each of these methods was based on a second order multiple regression, using all 24 locations with known weather data to solve for the 7 unknown coefficients. The regression equation took the form:

$$E = aL + b\Phi + cL\Phi + dL^2 + e\Phi^2 + fH + g \quad (9)$$

where,

H = elevation, ft.

The coefficient, f, was the linear correction factor accounting for temperature changes due to elevation, similar to the adiabatic lapse rate. The elevation correction established by this correlation of all 24 data points was applied to the inverse square distance method and to each of the interpolation methods by rearranging the appropriate equation (6-9) to give,

$$E - fH = \ldots \quad (10)$$

and solving for the coefficients as before. Adding back in the elevation correction for each location gave the estimated heating energy requirement corrected for elevation.

DISCUSSION OF RESULTS

Table 5 shows the standard deviations of the heating energy requirement predictions compared to BLAST predictions for each of the methods used. All standard deviations were based on the sum of the squared errors (or percent errors) between interpolation and BLAST predictions for the three houses in all 24 test sites (a total of 72 data points). **Figures 3 to 8** show plots of these predicted results against BLAST simulation results for the significant methods discussed.

The first observation was that the degree-day method was less accurate than any of the other methods compared. An important second observation was that the use of the linear correction for elevation produced a distinct improvement in most of the methods to which it was added.

Considering all the methods used, it was apparent that the choice of method depended on the number of locations with weather data for use in interpolation. If only three neighboring sites with weather data were available, then linear interpolation with elevation correction was best. If six or seven sites with weather data were available, then linear interpolation with elevation correction was still best even though second order interpolation was possible. If many weather sites (in this case, 24) were available then the second-order interpolation method with elevation correction was best.

Table 5. Standard Deviations(SD) of Predictive Methods from BLAST Simulation Data

Heating Energy Requirement Prediction Method	SD(error)	SD(% error)	Rank
Degree-Day Method	4.396 MMBTU	11.3%	16
Inverse Distance Weighting (3 sample pts)	2.725 MMBTU	7.5%	11
Inverse Square Distance Weighting (3 sample pts)	2.653 MMBTU	7.1%	10
Inverse Square Distance Weighting + Elevation Correction	2.516 MMBTU	6.9%	8
Linear Interpolation (3 sample pts)	3.033 MMBTU	9.1%	15
Linear Interpolation + Elevation Correction (3 sample pts)	2.210 MMBTU	6.6%	6
Linear Interpolation (7 sample pts)	2.603 MMBTU	7.1%	9
Linear Interpolation + Elevation Correction (7 sample pts)	1.762 MMBTU	5.2%	3
2nd Order Interpolation (6 sample pts)	2.176 MMBTU	6.7%	7
2nd Order Interpolation + Elevation Correction (6 sample pts)	3.087 MMBTU	8.9%	14
2nd Order Interpolation (7 sample pts)	2.734 MMBTU	8.1%	12
2nd Order Interpolation + Elevation Correction (7 sample pts)	3.017 MMBTU	8.9%	13
Linear Interpolation (24 sample pts)	2.318 MMBTU	6.1%	5
Linear Interpolation + Elevation Correction (24 sample pts)	1.569 MMBTU	4.6%	2
2nd Order Interpolation (24 sample pts)	2.149 MMBTU	6.1%	4
2nd Order Interpolation + Elevation Correction (24 sample pts)	1.360 MMBTU	3.9%	1

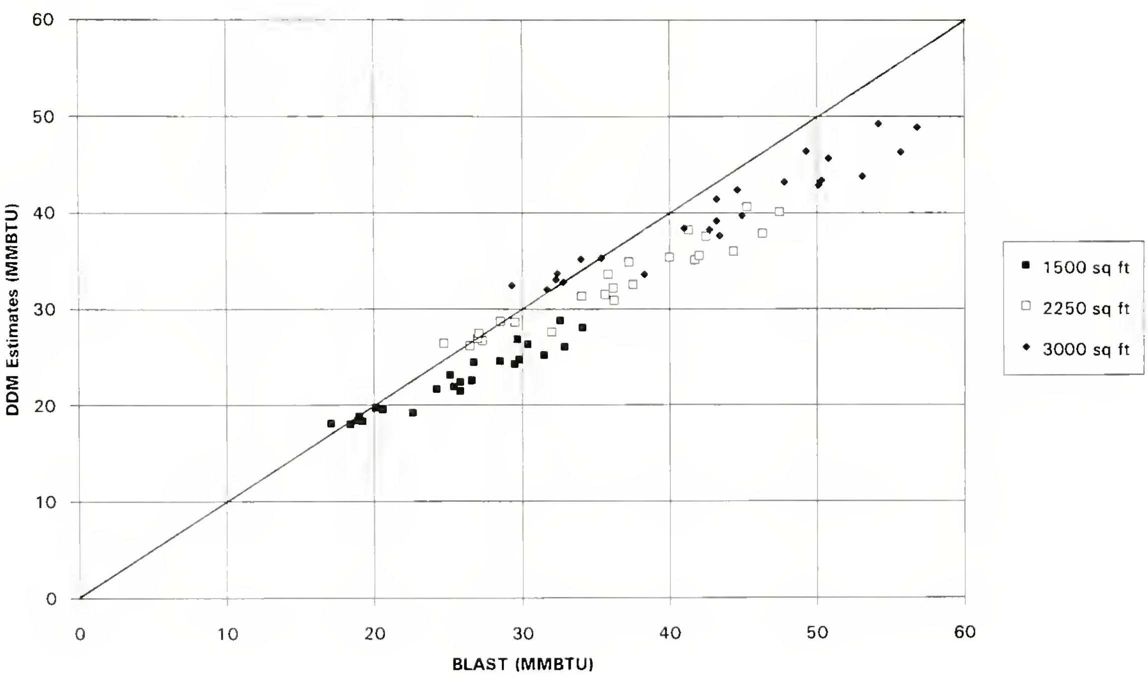


Figure 3. BLAST vs. Degree-Day Method

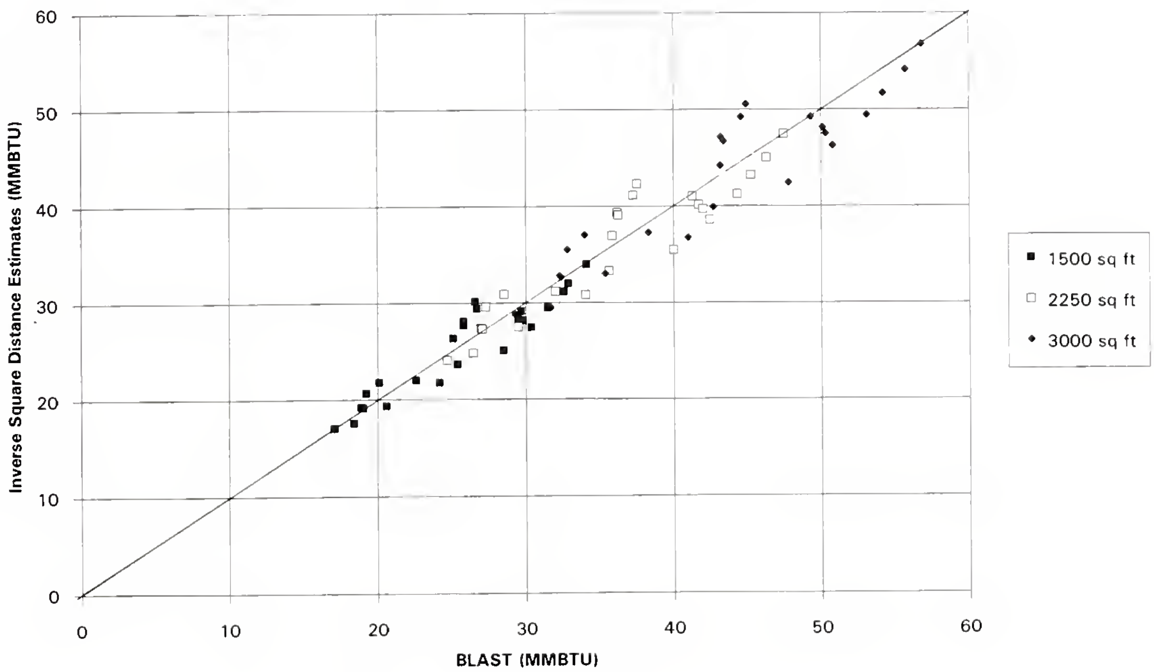


Figure 4. BLAST vs. Inverse Square Distance with Elevation Correction

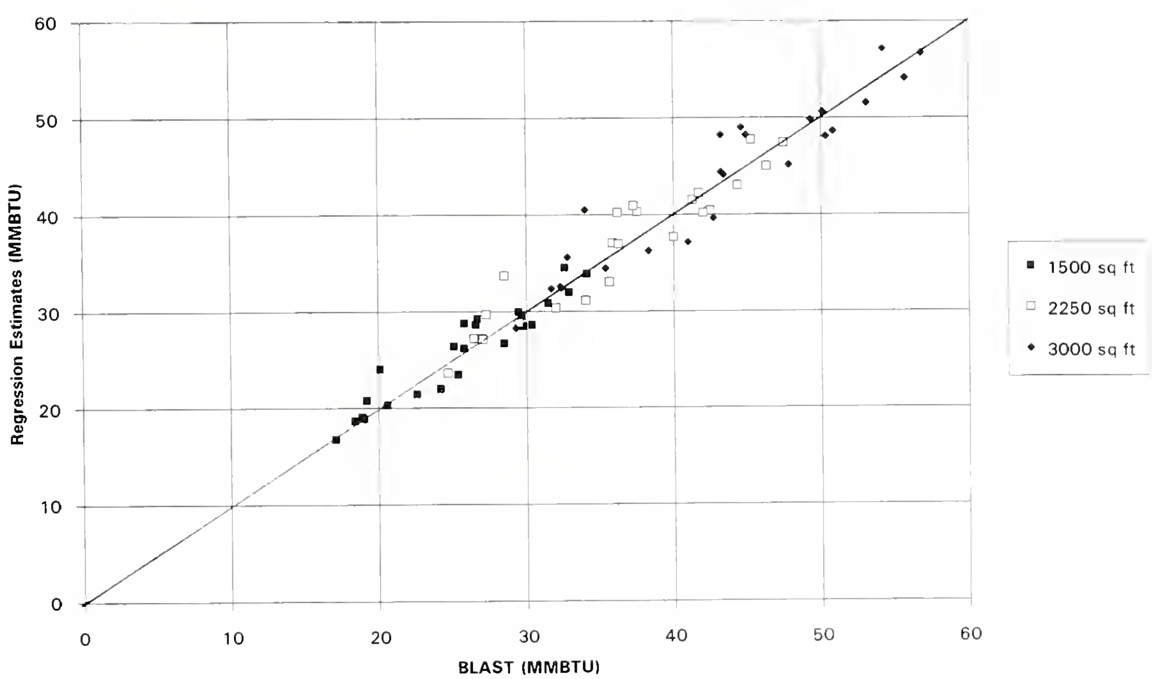


Figure 5. BLAST vs. Linear Interpolation with Elevation Correction (3 Sample Points)

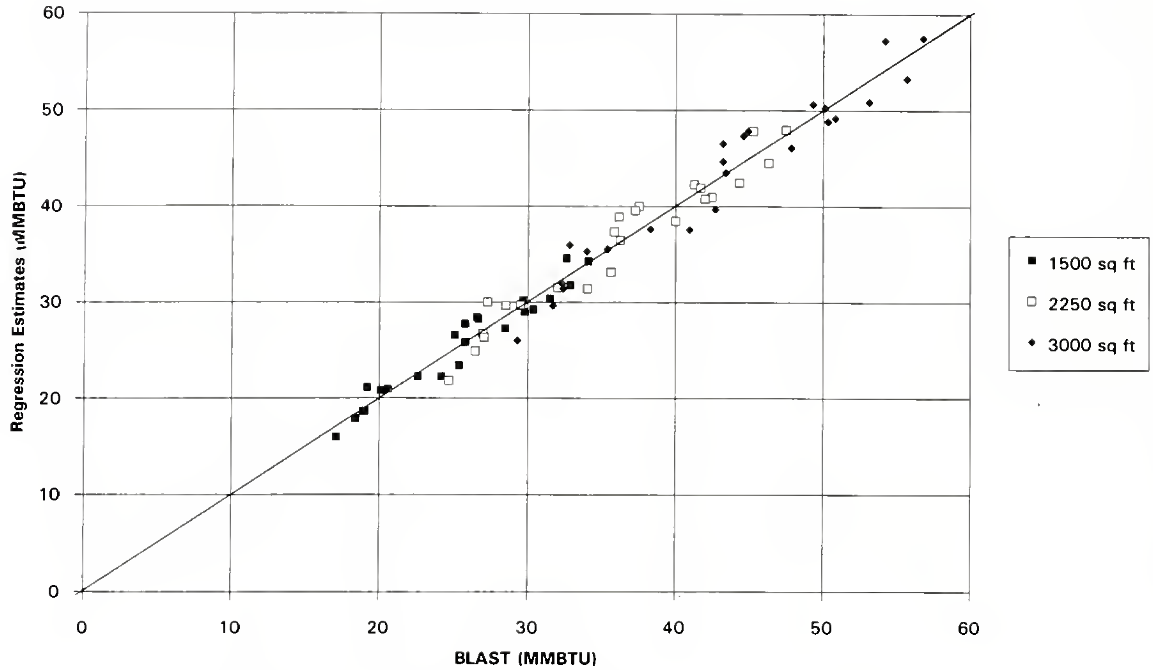


Figure 6. BLAST vs. Linear Interpolation with Elevation Carrection (7 Sample Points)

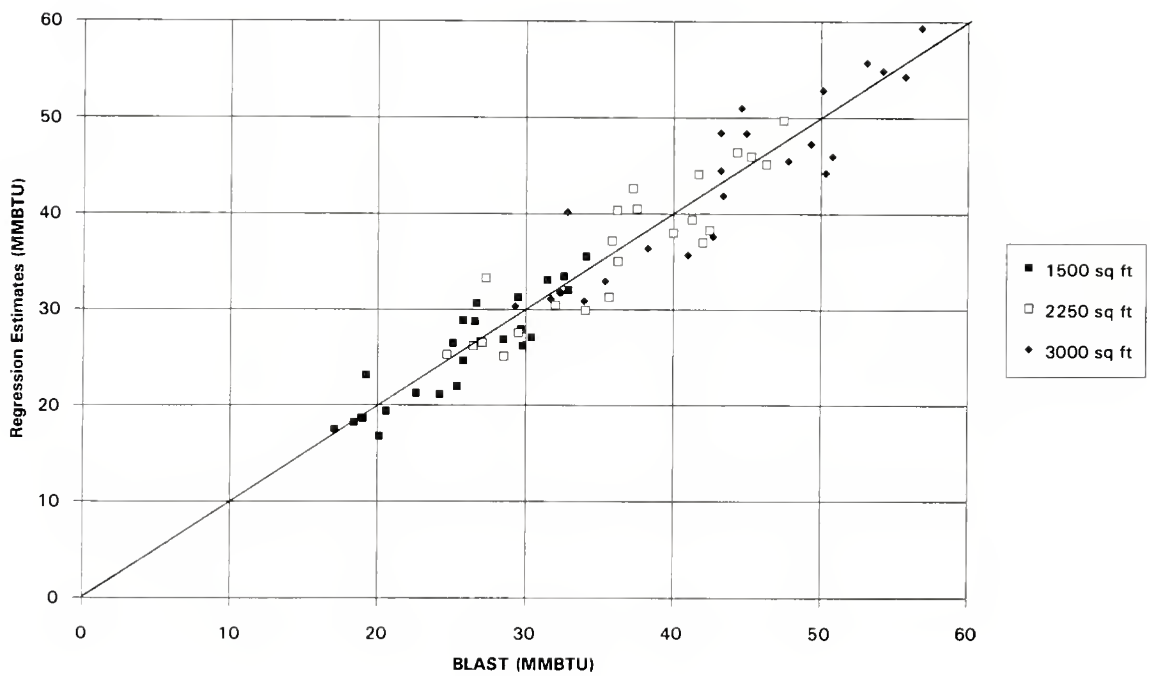


Figure 7. BLAST vs. 2nd Order Interpolation with Elevation Correction (7 Sample Points)

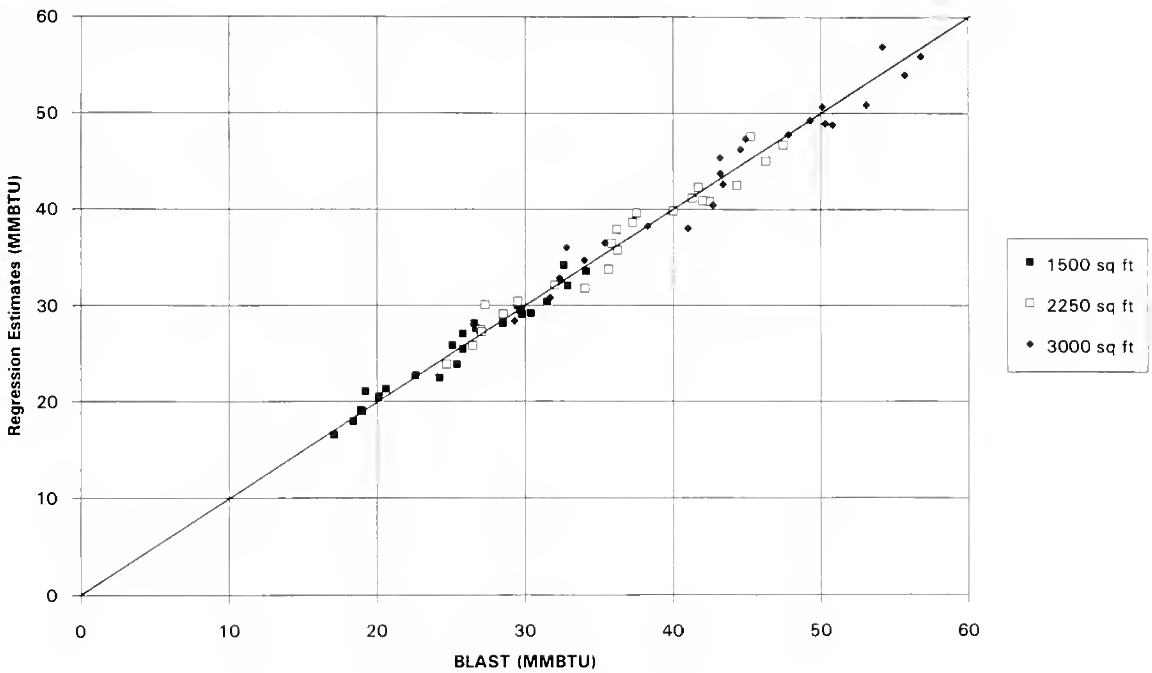


Figure 8. BLAST vs. 2nd Order Interpolation with Elevation Correction (24 Sample Points)

The standard deviations of the heating energy requirement predictions, based on interpolation from BLAST simulations at the same sites, ranged from four to seven percent for these best methods, depending on the number of neighboring sites with weather data used in the interpolations. These are minor errors compared with those introduced by imprecise house description and occupant preferences (thermostat settings, natural ventilation, appliance usage, etc.). Furthermore, these errors will be reduced in real applications because the interpolation sites used in this study will be available as reference locations which will move the set of reference sites closer together.

CONCLUSIONS

For design or research applications where building energy analysis computer programs are used, interpolation methods are superior to simplified heating energy calculation methods such as the degree-day method in locations where detailed weather data are not available. Performing multiple building energy analyses and applying the interpolation techniques described in this paper might seem time consuming. However, the primary task in building energy analysis is still the production of input data describing the house to the computer program. Running the program at multiple weather sites and then interpolating between them could easily be automated to produce heating energy use predictions at sites without weather data. Standard errors of four to seven percent are expected for the better interpolation methods, compared with over eleven percent for the degree-day method.

ACKNOWLEDGMENTS

This work was carried out with funding from the U. S. Department of Energy under DOE Research Project No. DE-FG41-92R110542, *Energy Efficient HVAC Systems for Modular Housing*. The assistance and support of the members of the project steering committee are also appreciated.

REFERENCES

Andersson, B., F. Bauman, and R. Kammerud. 1980. Verification of BLAST by comparison with direct gain test cell measurements. *Lawrence Berkeley Laboratory Report LBL-1-619*, UC-95d. Berkeley, California.

ASHRAE. 1989. *ASHRAE Handbook of Fundamentals*. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc. Atlanta, Georgia.

ASHRAE. 1993. *ASHRAE Handbook of Fundamentals*. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc. Atlanta, Georgia.

Bauman, F., B. Andersson, W.L. Carroll, R. Kammerud, and N.E. Friedman. 1983. Verification of BLAST by comparison with measurements of a solar-dominated test cell and a thermally massive building. ASME, *Journal of Solar Energy Engineering*, Vol. 105, 207-216.

BLAST Support Office. 1991. *BLAST User Reference*. Department of Mechanical and Industrial Engineering, University of Illinois. Urbana-Champaign, Illinois.

Burt, Hill, Kosar, Rittelmann Associates. 1992. *Final Report*, West Penn Power Company All-Electric Energy Efficient Demonstration House. Butler, Pennsylvania.

CGSB. 1986. Determination of the airtightness of building envelopes by the fan depressurization method. *CGSB Standard, 149.10-M86*. Canadian General Standards Board. Ottawa, Ontario.

Claridge, D.E., M. Bida, M. Krarti, H. Jeon, E. Hamzawi, W. Zwack, and I. Weiss. 1987. A validation study of variable-base degree-day heating calculations. *ASHRAE Transactions*, Vol. 93, Part 2, 57-89.

Fischer, R.D, L.J. Flanigan, S.G. Talbert, and D. Jaffe. 1982. Degree-days method for simplified energy analysis. *ASHRAE Transactions*, Vol. 88, Part 2, 522-571.

Herron, D., L. Windingland, and D. Hittle. 1980. Comparison of BLAST computer program simulations and measured energy use for Army buildings. Construction Engineering Research Laboratory, *U.S. Army Corps of Engineers Interim Report*, CERI-IR-E-161. Champaign, Illinois.

Mitalas, G.P. 1987. Calculation of below-grade residential heat loss: low-rise residential building procedure. *ASHRAE Transactions*, Vol. 93, Part 1.

Sherman, M.H. and M.P. Modera. 1986. Comparison of measured and predicted infiltration using the LBL infiltration model. In *Measured Air Leakage in Buildings*. ASTM STP 904, 325. H.R. Trechsel and P.L. Lagus, eds. American Society of Testing and Materials. Philadelphia, Pennsylvania.

Yuill, G.K. 1985. Verification of the BLAST computer program for two houses. *ASHRAE Conference Paper HI-85-13 No. 1*. Honolulu, Hawaii.

Yuill, G.K. 1986. The BLAST verification. *ASHRAE Journal*, Vol. 28, 62-70.

Yuill, G.K., and E.G. Phillips. 1981. Comparison of BLAST program predictions with the energy consumptions of two buildings. *ASHRAE Transactions*, Vol. 87, Part 1, 1200-1206.

Microbial Contamination of Building HVAC Systems: Causes And Solutions

Ossama A. Abdou and Francis A. Sando

ABSTRACT

Modern buildings today are experiencing indoor air quality (IAQ) problems. There are many causes of poor air quality, some of which are leading to a variety of building-related complaints. One of the main causes is indoor microbial contamination—bioaerosols—disseminated throughout the building by the air-conditioning system. Bioaerosols consist of viruses, bacteria and fungi, that thrive in moist areas. The air-conditioning system, with wet cooling coils and moist ducts, make ideal host reservoirs for these microrganisms. The most publicized bacterium associated with air-conditioning systems is *Legionella pneumophila* which causes Legionnaires' disease and Pontiac fever. *Legionella* strains have been found in water cooling towers associated with air-conditioning plants and in water spray systems. Saprophytic organisms such as *Aspergillus flavus* thrive in some nonliving plant substrates and can be pulled into a building through the fresh air intake grille of the air-conditioning system. They are known to have a carcinogenic effect. The extent of microbial contamination in building HVAC systems is described and remedial actions are proposed.

Today's air-conditioning system can no longer supply only heated or cooled air to provide occupant comfort, but also must provide systems to preserve the quality of the air we breathe. The system must have components to kill bioaerosols, as well as eliminate chemical and particulate contamination. A generic air-conditioning system, with such components shown, is proposed and diagramed in this paper.

Ossama A. Abdou is currently a faculty member in the Department of Civil and Architectural Engineering, Drexel University, Philadelphia, PA. His research interests center around building thermal energy analysis, building systems integration and indoor air quality control.

Francis A. Sando is research professor (retired) in the Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA. His research experience includes HVAC dynamic systems, indoor air quality control, low-temperature psychrometrics, desiccation and transient heat flow analysis.

INTRODUCTION

Indoor air pollution is an emerging problem which has been linked to energy conservation, the use of building materials and the design and operation of heating, ventilation and air-conditioning (HVAC) systems. Since a large amount of time—up to 90 percent—is spent indoors (EPA 1989; Chen et al. 1992), indoor air quality (IAQ) is an important factor to our health and comfort. IAQ problems and complaints are being increasingly reported (ACGIH 1984; ORNL 1985; Hodgson and Hess 1992) and have led to the classification of the following building sicknesses: sick building syndrome (SBS), building-related illness (BRI), and multiple-chemical sensitivity (MCS). Increased awareness of the potential health risks associated with indoor air contaminants arguably linked with significant lost annual worker productivity along with related worker claims and litigations, has stimulated the need to improve our understanding of how contaminants are transported in buildings. IAQ is a result of a complex relationship between the contamination sources in a building, the ventilation rate, sensitivity of various individuals to particular contaminants, and the dilution of the indoor air contaminant concentrations with outdoor air or treated recirculated air. This complex relation-

ship is further aggravated by outdoor sources used for dilution air and pollution sinks in a building that may amplify or act as a host for contaminants. One important implication of this is that building HVAC systems which create and control interior environments can promote or prevent and mitigate indoor air contamination through their design, operation and maintenance.

CAUSES OF BUILDING SICKNESS

Firstly, the term SBS is a misnomer, because the buildings are not sick, although occupants of such buildings exhibit symptoms associated with being ill. The World Health Organization identifies a range of symptoms for SBS which cause distress to some building occupants, but cannot be clinically diagnosed and, therefore, cannot be medically treated. Typically, in such a case, a building's occupants exhibit discomfort or dissatisfaction with the environment other than feeling too warm or too cold. Occupant discomfort is usually evidenced by symptoms such as headache, fatigue, sinus congestion, sore throats, and eye irritation. The occupants experience relief almost immediately after they exit the building and the symptoms disappear when the sufferers leave the building for the weekend. Usually, the symptoms recur upon re-entry.

This definition of SBS implies that sensory irritation must be a dominant complaint while systemic symptoms should be infrequent. It further implies that the prevalence of the symptoms should be so great that the reactions are clearly related to an unfavorable indoor environment and not caused by any medical conditions among the occupants. Unless the dissatisfaction level is around 20 percent of the occupants, the problems are not likely to be considered as SBS, and if the percentage dissatisfied rises above 20 percent in one part of the building, where the environment is said to be common throughout, the problem is probably much more mundane.

BRI, on the other hand, refers to an illness caused as a result of exposure to an indoor air agent that can be identified. As it is commonly used, the term BRI refers to an illness outbreak among building occupants (e.g., individuals entering a building for extended periods, and those residing and working in a particular building), with no secondary spread of the illness to others outside the building with whom affected individuals come into contact. Symptoms include infection, hypersensitivity pneumonitis (HP), etc. MCS refers to high sensitivity to chemically-based pollutants in the environment.

Building sicknesses (especially SBS) have been initially ascribed to inadequate ventilation—either because of increased envelope tightness or decreased introduction of outdoor air into a building space. A number of other factors have been identified as causing sickness of occupants. These include exposure to bioaerosols, volatile organic compounds (VOCs), unpleasant odors, smoke, chemicals and particulates found in the air of both naturally and mechanically ventilated buildings. One class of indoor air pollutants are biological contaminants that thrive in moist areas, including air-conditioning systems. Major causative agents contributing to a large number of "sick buildings" have been reported as being primarily fungal and bacterial contamination (Cunningham 1989). Fungi generate not only spores, but also release toxic compounds and VOCs in the air. Since these organisms are being implicated in an increasing number of problem buildings, not only a better understanding of their nature, habitat and control is warranted, but also remedial actions are to be sought to mitigate and eventually eradicate the problem of microbial contamination in building HVAC systems.

It is important to recognize that microbial contamination can occur in a building through sources other than the HVAC system. For example, flooding, roof leaks and some janitorial practices (e.g., carpet shampooing) have been referred to as contributing to such microbiological growth in building spaces. The existence of microbial indoor air pollutants is almost always evidence that the building's maintenance or repair procedures are lacking in some respect.

MICROBIAL CONTAMINATION

Microbial contamination is a catch-all term for any bioaerosol consisting of airborne particles, viruses, bacteria, fungi, oversized mole-

cules or volatiles which are living or released into the air by some living organism. Bioaerosols include vegetative microbial cells, their reproductive units and metabolites that are small enough or sufficiently volatile to achieve aerial dispersion. Bioaerosols range widely in size, from less than 0.1 micron to greater than 100 microns. Three conditions are usually necessary to release them into the air, a *reservoir, amplification* or a means to increase their concentration, and *dissemination*. Domestic animals, birds, and humans emit organisms or effluents which can easily act as reservoirs and amplifiers. The other conditions, amplification and dissemination, occur from the living host. Influenza, a respiratory infection, is typically spread in this manner.

Levels of bacteria and fungi in air are measured in terms of colony forming units (CFU)/m^3 or in concentrations of magnitude/mL. A colony typically consists of 10^6 to 10^7 cells. Magnitudes of 100 CFU/m^3 or less for some bacteria are considered low. *Indoor* concentrations of as high as 100,000 CFU/m^3 are not uncommon in large buildings (Morey 1988a). The most common *outdoor* composition of airborne fungi are as follows: *Cladosporium sp., Penicillium sp., Alternaria sp. and Aspergillus sp.* Other predominant microorganisms include *Rhodotorula sp., Legionella pneumophila, Aureobasidium sp., Acanthamoeba polyphaga* and *Thermoactinomyces* (Hodgson et al. 1985). The transport mechanism for viruses is by means of droplets (e.g., generated by sneezing or coughing) or clinging to dust particles.

The most publicized bacterium associated with air-conditioning systems is *Legionella pneumophila*, which causes Legionnaires' disease and Pontiac fever. More than 25 species of this bacterium have now been recognized with many more serotypes. The bacterium occurs in nature in moist soil or tepid water—up to 50 percent of the bodies of water in the US are believed to contain *Legionella* strains (Hodgson and Hess 1992)—and has been found in water cooling towers associated with air-conditioning plants and in water spray systems which form part of some air-conditioning equipment. *Legionella* must have a water substrate to live, and it can be dangerous if water droplets are picked up by the HVAC system and carried into an occupied space. The level of risk to occupants is still considered to be small, although a number of fatalities have been reported. Certain conditions for the growth of *Legionella pneumophila* are necessary, and although they can be found in bodies of water ranging in temperature up to 140°F (60°C), significant multiplication is generally restricted to temperatures of 68°F (20°C) to 115°F (46°C). Some investigators have proposed a practical working level of 10,000 *Legionella pneumophila* per milliliter, above which serious consideration should be given to cleaning and chemical disinfection (Fliermans and Nygren 1987).

Microbial sampling undertaken in a number of studies has shown that the concentration of fungi present in indoor air can be higher than that found outdoors by an order of magnitude or more. This, in turn, suggests that internal sources of fungi exist and are commonly attributed to incursion of moisture into various components within the space (e.g., carpets, ceiling tiles, upholstered furniture, wall partitions and office materials) or to the HVAC system itself as described below. A few large-scale studies have been published and have demonstrated that the complaints and symptoms are more frequent in buildings with mechanical ventilation (Mendell and Smith 1990). On the other hand, mechanical ventilation is usually associated with a lowering of the indoor concentration of airborne fungi compared with levels encountered outdoors or in naturally ventilated spaces (Hirsch et al 1978; Rose and Hirsch 1979; Solomon et al. 1980). **Table 1** lists a few of the fungi which can affect building occupants by collecting near fresh air intakes, at filters, near cooling coils or within the building occupied space.

Because of the many bioaerosols that can contaminate the air we breathe and make us sick, the air handling units (AHU) and ductwork of a building air-conditioning system are now coming under scrutiny. Is the air-conditioning system a reservoir or an amplifier? It certainly could be a disseminator since it is delivering air to (and collecting air from) occupied spaces.

Table 1. Sources and Health Efects of Fungi Commonly Found in Buildings

Organism	Causal Part	Main Sources	Health Effects
Aspergillus	Spores	Damp organic material; Self-heated compost	Invasive aspergillosis; Aspergilloma; Allergic bronchopulmonary aspergillosis (ABPA)
Aspergillus Penicillium Sporobolomyces	Spores	Damp organic material; Standing water	Hypersensitivity pneumonitis (HP)
All airborne fungi spores	Spores	Damo organic material; Outdoor air	Allergic asthma; Rhinitis
Aspergillus flavus	Toxin	Agricultural products	Cancer
Cryptococcus	Spores	Bird droppings	Cryptococcosis
Histoplasma	Spores	Bird droppings	Histoplasmosis
Penicillium species	VOC	Damp organic material	Irritants
Stachybotrys atra	Toxin	Damp cellulosic material	Acute Toxicosis
Ulocladium	VOC	Damp organic material	Headache

MICROBIAL PROLIFERATION THROUGH HVAC SYSTEMS

Microbial contaminants usually are brought from their sources to the occupied space by means of an airstream. Inside a building, contaminants are distributed from their sources by means of natural convection or the ventilation system itself. Many studies show that ventilation systems play a major role in IAQ problems. Over 50 percent of all IAQ problems investigated over an 18 year period by the National Institute for Occupational Safety and Health (NIOSH) have been attributed to ventilation deficiencies (Moseley 1990). Regulation of fresh air quantities and air movement is suggested as a measure in alleviating most reoccurrences of SBS. It also appears that air flow patterns in a building may have a significant influence on the spreading of airborne bacteria and viruses. This emphasizes the importance of ventilation effectiveness (whether mechanical or natural) in buildings. On the other hand, since the primary requirement for the growth and amplification of microorganisms in the indoor environment is the presence of moisture, contamination can occur in a building regardless of the amount of outdoor air being supplied to the space. The exact number of problem buildings with microbial contamination is not known; however, it is estimated that these can be as high as 33 percent (Wallingford 1986) (HBI 1990).

Microbial contaminants in the indoor environment may cause illnesses of two general types, namely, those that are *infective* and those that are *allergic* in nature. Many of these illnesses occur as a response to antigens aerosolized from HVAC system components such as humidifiers or air washers which may be contaminated (Edwards 1980; Scully et al. 1979). Other sources of reported illnesses are from other building components that have been damaged by recurrent floods or other sources of moisture (Morey 1988a).

The presence of microbes in the indoor environment in sufficient amounts or types to cause illnesses depends on a number of factors:

- type of mechanical components that constitute the HVAC system;
- maintenance plan for mechanical systems; and
- the presence of water.

Water is the primary factor permitting microbial contamination. Since absence of water or moisture is virtually impossible in any HVAC system, the AHUs of such systems offer

ideal environments for microbial proliferation. HVAC systems must function to provide an environment where temperature, air distribution, humidity and IAQ are maintained within the described levels. For the most part, HVAC systems are designed to mix a given amount of outdoor air with another amount of recirculated air, condition this mixture, and distribute it to the occupied space. By mixing outdoor air with recirculated air, dilution of pathogenic bacteria is possible as well as reduction of chemical vitiation.

Outdoor air entering the building may be contaminated by nearby sources of bioaerosols such as those from cooling towers, evaporative condensers, toilet exhausts and sanitary vents. Cooling system components are especially known to harbor microorganisms which can cause a variety of problems, including loss of heat transfer efficiency and deterioration of system components. They have further been implicated in the growth and dissemination of pathogenic microorganisms. Thus, a HVAC system may serve to transport microorganisms from the locus of contamination to the vicinity of sensitive occupants. The air exiting the mixing plenum of the AHUs passes through filters. These filters, depending on their efficiency, are poor collectors of small spores that might be entering the AHU from an outdoor source such as dead vegetation. The filtered mixture of outdoor and return air passes through the coil section where it is heated or cooled to meet the specified requirements. Conditioned air is then supplied to the building spaces. This is shown conceptually in **Figure 1**. A schematic diagram of a blow-through air handler in which the fan is located upstream of the heating and cooling coils is given in **Figure 2**.

During the summer season, moisture condenses from the air stream as it passes through the cooling coils [which usually maintain a 42-55°F (6-13°C) chilled water system temperature or a 30 to 45°F (-1 to 7°C) surface temperature of a DX system]. When the coil surface temperature is below the dewpoint of the air stream, condensed water collects in a drain pan and exits the AHU through drain lines. In many cases, water stagnates in the drain pans; hence, the pan becomes a potential reservoir and amplification site for microbes. Furthermore, air washer type humidifiers located downstream from filter banks and near heating and cooling coils operate by aerosolizing water into the air stream. Water that is not taken up by the air stream falls into a sump and is circulated to nozzles for re-aerosolization. This type of humidification system is particularly subject to extensive microbial contamination as well as being an ineffective

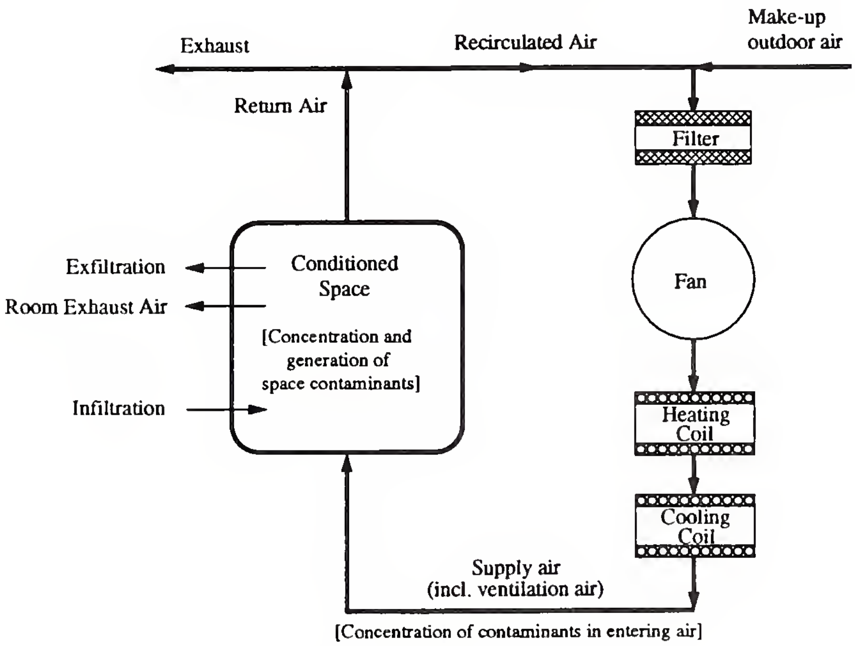


Figure 1. Concept of a typical HVAC system

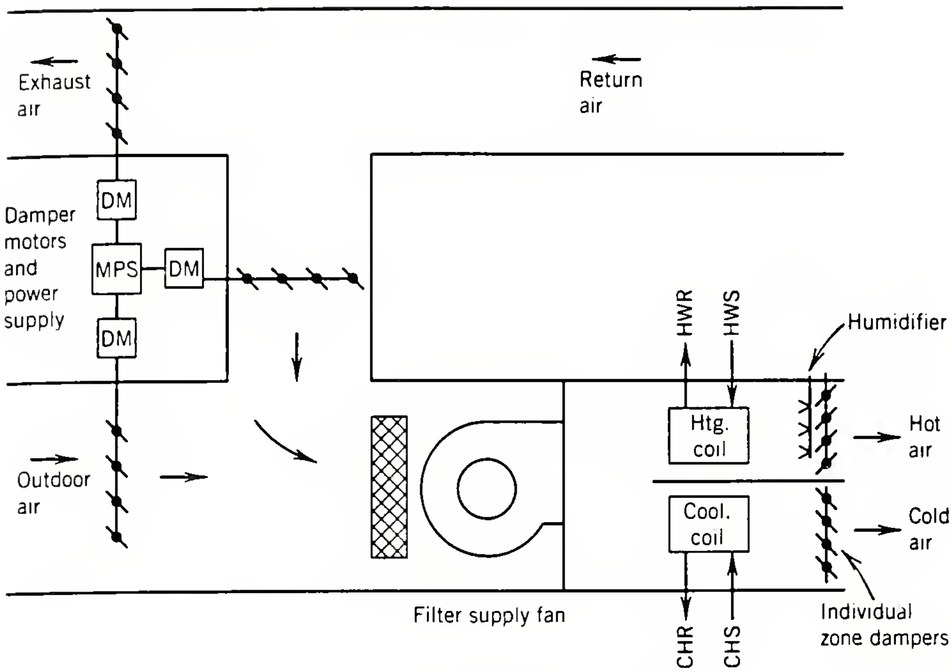


Figure 2. Schemotic of a blow-through air handler

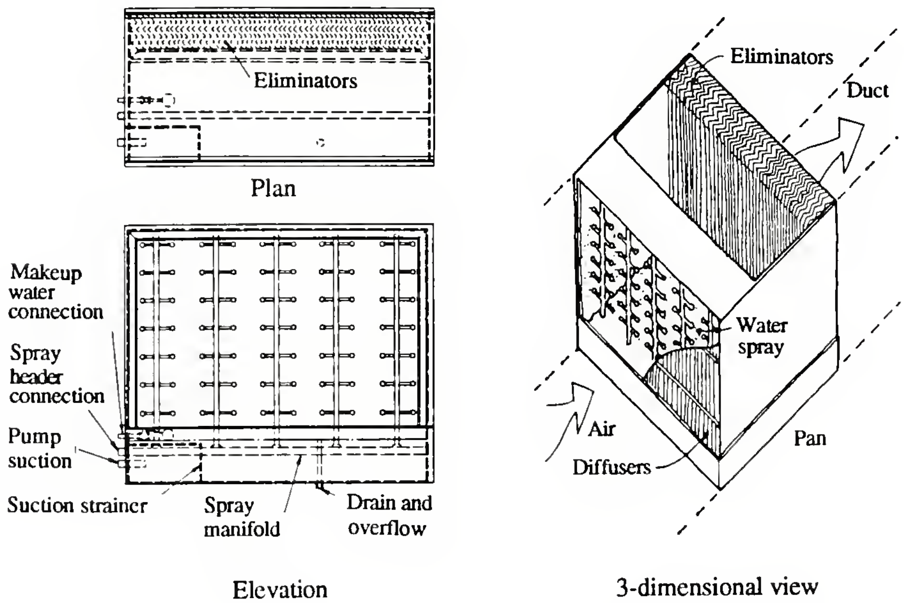


Figure 3. Conventional spray-type air washer

way to humidify air. In **Figure 3** a typical air washer is illustrated.

Conditioned air leaving the AHU fan plenum is transported to the space by a system of ducts. Conditioned air from the AHU enters the space through grilles or diffusers and mixes with room air. Mixed air is then pulled out of the space either through a return duct or through a common return plenum and is then partially removed by the return fan and is partially exhausted. Because of difficulty in access-

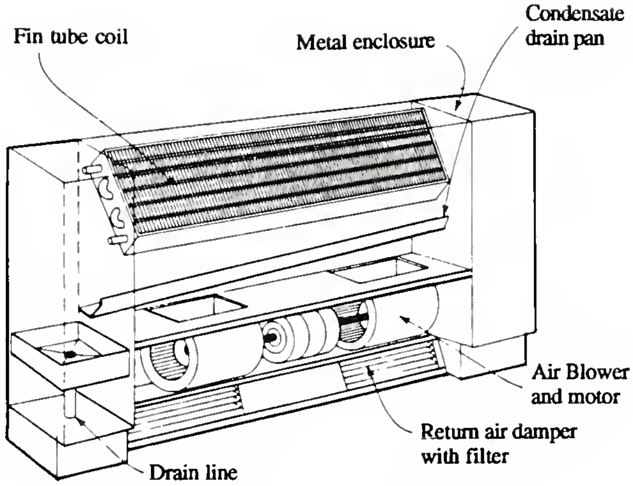


Figure 4. Typical fan coil unit (below window type)

ing the return plenum and ducts for proper maintenance, microbial contamination that may occur is removed only with great difficulty. Ducts that have been installed and operating for ten to twenty years without cleaning are probably loaded with dust and dust mites. Ceiling plenums are particularly susceptible to dust and fibers which are then pulled into the return duct connecting to the AHU.

The heating and cooling load of a large building may be handled by fan coil units installed at the periphery of the building. Each unit consists of low-efficiency filters, a fan, a heating and cooling coil and a drain pan. Water may accumulate in the pan and create a microbial slime. **Figure 4** shows a typical fan coil unit depicting the location of the drain pan. Porous insulation liners applied to the inside of the fan coil units for sound attenuation provide an additional substrate for microbial growth. Dirt and debris accumulate within the insulation and microorganisms may flourish on this substrate when it becomes moist during the air-conditioning mode of operation. If mold or slime is visible, then fungi are present.

INDOOR MICROBIAL EXPOSURE LEVEL

No scientifically based criteria exist to show whether a measured level of fungi or bacteria is a risk factor with regard to any allergic diseases. Therefore, a carefully thought-out and planned approach must be used to determine these risks. Any quantitative criteria must take into account the qualitative nature of the diverse viable and nonviable etiologic agents thought to be responsible for these illnesses. Several suggestions have been made concerning normal or hygienically acceptable levels of airborne viable particulates found in large buildings and, in particular, large office environments. A level of approximately 1,775 bacteria-containing particles/m^3 was described as the threshold for clerical environments in need of investigation and hygienic improvement (Bourdillon et al. 1948). Others suggested that this threshold be 1000 CFU/m^3 (Morey et al. 1984). Levels of about 700 bacteria/m^3 were considered more normal, and it has been stated that levels of viable microorganisms in the indoor environment seldom exceed 1,700/m^3 (Wright et al. 1969). Other studies indicate that levels of viable particulates in office spaces with HVAC systems normally range from 100 to 300 CFU/m^3 (Yoshizawa and Sugawara 1985). The ACGIH (1989) has developed an approach that bases the allowable indoor contaminant level on existing outdoor levels.

In reporting on a study on fungi in Canadian houses, Miller et al. (1988) proposed the following criteria of acceptability for fungal pollution in indoor air: More than 50 CFU/m^3 should be reason for concern if there is only one species present, while less than 150 CFU/m^3 should be considered acceptable if there is a mixture of species, and less than 300 CFU/m^3 should be acceptable if the species present are primarily *Cladosporium* or other common phylloplane fungi. More recently, a study recommended

that the airborne microbe levels be between 250 and 750 CFU/m^3 (HBI 1991) to avoid any health hazards. Another study indicates that a factor defining indoor contamination includes indoor bioaerosol levels being consistently more than double levels outdoors and exceeding 1000 spores/m^3 of air (Burge 1990). Nonetheless, many studies point to the inappropriateness of using any given level or concentration of viable particulates as the sole indicator of an illness threshold (Morey 1988a).

A Norwegian Health Directorate Report (1990) indicated a very general or rather vague threshold, characterizing exposure limits for microorganisms. It simply stated that a mouldy smell should not occur. There is no question that using the sense of smell as a tool to identify maximum contaminant limits is a practice fraught with inaccuracies as well as uncertainties.

It is indeed interesting to note that despite much research, the direct relationship between many pollutants and health problems cannot be proven. However, there is sufficient evidence to warrant some action in controlling the levels of microbial contaminants. For example, it has been reported that the levels of contamination posed a danger in 27 percent of "sick buildings" investigated as a result of excessive fungal contamination and in 25 percent as a result of excessive bacterial contamination (Cunningham 1989). There is some correlation between concentration levels of microbial pollutants and mortality and illness rates. Nevertheless, no single pollutant has been singled out as being responsible. Further research is proceeding to quantify the risks and identify those parameters which influence risk. Since most microbial contaminants affect the human body by means of the respiratory system and most fungi are facultative parasites, there is a close link between the HVAC system, air quality and complaints about SBS. It is suggested that there is a synergistic association among a number of factors including multiple exposure levels to pollutants and an individual's general state of health.

MICROBIAL CONTROL IN HVAC SYSTEMS

Microbes are ubiquitous in nature and are normally found on environmental surfaces. They enter a building in many ways, and indeed may be built into it, because construction dust and debris may contaminate HVAC system components at the time of their installation. Since microbes and their spores are small and light enough to be carried with air currents, the outside air taken into a building always contains large numbers of them. The outdoor air intake of an HVAC system should, therefore, be protected with a filter or a grille of fine mesh to prevent organic materials from being drawn in, these materials being particularly potent in microbial contamination.

The ventilation system in the building provides the first line of defense in arresting microbes. The return air, drawn back to the air handling unit, may be heavily laden with airborne particulates and microbes. A properly designed and maintained system will have the return air diluted with outdoor air and both will be efficiently filtered to reduce the microbe content. In many cases, however, the filtration systems are poorly designed and installed and, above all, badly maintained. This allows microorganisms (especially fungi) to amplify and contaminate the air supply system. Standing water around cooling coils, condensate trays, humidifiers and condensation water in ducts, fan chambers and on insulation surfaces, then become contaminated and allow further proliferation of growth. The ventilating system itself then provides a means of transporting more spores into the occupied areas. Based on the above, prevention from infestation is of paramount importance. Many "spray-on" antimicrobials are currently in use; few of them, however, give durable protection since spray-on compounds wear off with use, or they become ineffective when cleaned or exposed to moisture. Moreover, sprays themselves use aerosol propellants or contain components which increase the chemical burden of the indoor air with potentially dangerous VOCs.

Several researchers have investigated the efficacy of biocides in controlling microorganisms in HVAC system components, especially in cooling tower environments. For example, a study demonstrated that a number of biocides kill a variety of microbes habitating building cooling systems including *Legionella* when tested in a laboratory environment (Soracco et al. 1983). Another study showed, however, that some of these same biocides are not as effective in real

world situations (Soracco and Pope 1983), especially when concentrations of these chemicals are reduced in the water. Nonetheless, it is argued that continuous treatment with biocides that are effective at low levels may be a viable treatment option (Pope and Dziewulski 1992). However, the economics of a continuous biocidal treatment have not yet been established.

A study demonstrated that ozone, if properly applied, could affect control of microbial populations, including *Legionella*, in a variety of cooling systems (Pope et al. 1984). Of course, the degree to which microbial communities in the HVAC system can, or should be, controlled is opinionated. Some investigators are of the opinion that maintaining a system in a totally sterile condition is impractical if not impossible, let alone economical. Instead, the target should rather be to keep the microorganisms under control and to limit their effects on operation of the system. Experience shows that this is not an easy task given the high growth rate of microbes and the non-existence of any standard threshold limit values for microbial exposure levels.

REMEDIAL ACTIONS

Environmental factors that contribute significantly to indoor bioaerosol problems include the microbial content of the outdoor air (which is never completely free of microbial elements), ventilation mode, indoor occupant density and ventilation rate, and the presence of excessive heat and moisture in the indoor environment. A number of remedial actions are available that can effectively reduce or control indoor microbial contamination through the HVAC system.

Three methods of air quality control can be identified: source control, removal control and dilution control or clean up. The former can be implemented through isolation, containment and local exhaust while dilution control is a means of reducing the concentrations of contaminants in the environment by exchanging the room air with non-contaminated air or with air of less concentration of the contaminant. Removal control is implemented via air cleaning devices placed in the circulating airstream of an air-conditioned or mechanically ventilated space and it is usually the only means available when it is necessary to control the environment at concentrations below those of the outdoor air. Among the three control methods, source control is the only means to prevent exposure to a contaminant altogether while in the other control methods exposure to the contaminant is occurring or assumed. In other words, only source control can *eliminate* exposure of the contaminant; the other two methods inherently require mixture of the contaminant with the indoor air before any control methods are applied. Removal can also mean inactivating the air-conditioning system and physically washing the system with a biocide.

Remedial measures apply primarily to existing systems, and such systems can take two forms:

- Preserve the inside occupied space free from contamination; and
- Clean up existing contamination.

A third measure, applying to new construction, requires design professionals to design buildings and mechanical systems to prevent indoor air quality deterioration. Architects and mechanical engineers must work together at the conceptual stage to design and install HVAC equipment and ductwork in such a way that bacteria and fungi cannot get a foothold for growth within the mechanical system or the inside building substrate.

The ability of a ventilation system to control the concentrations of contaminants within acceptable levels at the exposure site of the occupants is highly dependent on the air distribution patterns both within and between functional spaces. In some spaces, natural ventilation may be the primary method of dilution control. In most cases, the primary method of control is mechanical ventilation. In either case, the effectiveness of the system for air quality control is dependent upon the system characteristics, the room air exchange rate and the uniformity of the airflow patterns within the room. If the room air distribution is not sufficient to dilute or remove contaminants from the location of most likely exposure, the effectiveness of the system will be impaired. Thus, the air distribution patterns within the room may be as important to the effectiveness of the ventilation system as the room air exchange

rate. Systems which characteristically provide little air movement (some VAV systems) can exacerbate contamination by bioaerosols.

Certain heating systems may, by virtue of their operation, be more inviting to microbial contamination than others. For example, forced-air heating systems may allow accumulation of spores in ductwork and produce bioaerosols by subsequent reflotation of such particles, as well as particles contained in settled dust within the living space. In contrast, radiant heat imposes neither such inaccessible ductwork nor the brisk air movement (i.e., ventilation) presented by forced-air systems. Heating systems based on combustion of fossil fuels exhaust potentially toxic combustion products to the outside and may cause substantial outside air to infiltrate into a building through cracks.

Preservation of uncontaminated space

How can the inside space be kept free of contamination? The answer is by applying most of the design parameters engineers are familiar with today, plus applying a few "new" ones which are mostly common sense. Design parameters engineers already know are outlined below:

- Use adequate filtration. Filters 50 to 70 percent efficient (based on ASHRAE standards) will remove most microorganisms from the air stream since they are usually up to 5 microns in diameter. The use of upstream inexpensive roughing prefilters extend the life of the filters.

- Keep the building under positive pressure to reduce contamination entering through building envelope cracks and crevices.

- Use outdoor air to dilute vitiation caused by air recirculation. Energy costs for heating and cooling outdoor air can be significantly lowered by using an air-to-air heat exchanger or run-around coils. The use of "cooling wheels" is questionable, since microbial contamination can easily be transferred along with heat.

- Locate fresh air intakes remote from cooling towers, evaporative condensers, toilet room exhaust ducts, sanitary plumbing vents, industrial exhaust fans, rotating or gravity exhaust vents, process equipment vent ducts, pressure relief valve stack heads, pathology room exhausts, autoclave exhausts, or any other hospital exhaust ducts. Moreover, the fresh air intake should be located upwind from all exhaust ducts.

- Humidifiers should be steam, located downstream from a pressure reducing valve to take advantage of superheat, and generated from a special small boiler or a heating plant boiler free from water treatment chemicals. The use of water sprays in air washers should be eliminated as these units have been associated with several outbreaks of allergic diseases (Arnow et al. 1978) as water/microbial aerosols migrate from water spray systems into ductwork and occupied spaces.

- Operate cooling systems to provide 40 to 60 percent relative humidity (RH) all year if possible. If necessary, reheat with heating coils even during summer to stay within this range. Many pathogenic bacteria do not like the 50 percent RH and will expire. Relative humidity in occupied spaces should certainly not exceed 70 percent to avoid fungal spore germination and proliferation (Brundrett and Onions 1980). Inappropriately high relative humidity will lead not only to condensation on cool surfaces but also will allow hygroscopic materials in the environment (e.g., human skin scales) to absorb enough water to facilitate microbial growth. Cooling coils of AHUs should be run at a low enough temperature to dehumidify conditioned air. Stagnant water should not be allowed to accumulate under cooling coils in AHUs. Proper inclination and continuous drainage of drain pans is necessary.

Clean-up of existing contamination

Once contamination has occurred, two approaches are available; air cleaning and surface and source decontamination. Clean-up of existing contaminated HVAC systems and occupied spaces usually consists of inactivating the air-conditioning system and applying disinfectants to all contaminated building spaces as well as ductwork, coils, inside surfaces of AHUs, fans and other equipment in the air stream. Washing microbially-contaminated hard surfaces with 5-10 percent bleach solution will kill resident microorganisms but will not prevent recontamination unless underlying conditions are changed. Other cleaning procedures include the use of biocides. These procedures often pose safety questions. Many biocides used in indoor environments will enter the air of the occupied space and may pose greater risks than the microorganisms that they are designed to kill. New biocides that are firmly attached to the treated substrate demonstrate promise but have to be adequately tested before use on a large scale (Burge 1990). Biocide activity increases with temperature and should be applied for a period of one to three hours, depending on its type. Biocide types include: Phenolics, alcohol, hydrogen peroxide, iodine, glutaraldehyde, quaternary ammonium (quats), hypochlorites and formaldehyde (a possible carcinogen). There are many other biocides which are used for special applications such as cooling towers (halogenated nitropropane, ethylene dichlorites, carabamates and sodium hypochlorites). The biocide should be registered and meet FDA and EPA standards. Biocides are regulated by EPA's Environmental Pesticide Act.

Cleaning techniques vary widely but can be generalized as follows:

- Inactivate the HVAC system.
- Vacuum with a cleaner and equipment which discharges outside the building.
- Remove contamination by cleaning with a detergent.
- Apply steam cleaning to contaminated areas.
- Apply biocide in accordance with directions approved by the appropriate agency. Be certain that the biocide is not aerosolized and spread to occupied spaces.
- Flush with an inactivator after the proper application interval is completed.

"New" common sense parameters:

Eliminate all underground ductwork. Underground ducts, along with ducts constructed of organic or insulation type materials, have been the cause of serious contamination conditions. Ducts can easily become contaminated with pathogens (e.g., hospital operating rooms) in a wet, underground environment, and are practically impossible to clean. Ductwork within buildings may be less prone to such contamination. If, however, underground ductwork cannot be eliminated, special attention should be given to moisture and substrate control in ductwork.

Preventive maintenance. The ventilation system should be carefully examined for appropriate design, operation and maintenance. For example, indoor microbial contamination can result when, for energy conservation purposes, chilled water systems are run at temperatures too high to provide adequate dehumidification. Likewise, "economizer" systems, designed to increase the amount of outside air brought into the system during mild weather, may be set so that more than minimum fresh air is delivered during hot and cold weather. Keeping all parts of the ventilation system clean is of paramount importance.

If the indoor environment is kept clean and ductwork is carefully cleaned by experienced workers, conditions necessary for microbial growth cannot occur. The AHUs should be constructed or modified so that maintenance personnel have easy access to the heat exchange components as well as to drain pans. Access doors should be strategically placed in all AHUs. The emphasis should be placed upon cleaning ducts. Although many buildings receive excellent daily housekeeping, ducts and AHUs may not have been touched since the HVAC equipment was installed. Filters usually receive attention, at least every six months, but coils are often partially clogged, green or black

mold and fungi may be growing rapaciously on the coils or drain pan. Aerosolization can easily occur when the growth is sufficient, and if the fungus is a facultative parasite (i.e., *Aspergillus, Cryptococcus* or *Mucor)*, it can use any other living organism (even a person) as a host. Even if contamination of occupants has not occurred, fungi produce metabolic substances that adversely affect the indoor environment. Biocidal mycotoxins are carcinogenic fungal metabolites. In addition, as indicated earlier, fungi can produce toxic chemicals and emit VOCs as they digest substrates.

The maintenance program should also include the regular checking of all temperature (and humidity) control settings and their performance; routine servicing of the HVAC plant; and regulation of fresh air quantities, air movement and air distribution.

Test for bioaerosols frequently. Such tests focus on environmental determinants of bioaerosols, including contributions from outdoor aerosols, ventilation mode and rate, and factors allowing intrusion or accumulation of moisture indoors. The nature of the landscape can affect levels of airborne spores immediately surrounding a building, especially low-rise and large buildings with air intakes near the ground. Dense vegetation close to a building may increase the risk of microbial contamination within (Kozak et al. 1978). Also, farming activities produce dense bioaerosols that can penetrate nearby buildings (Burge 1990).

Install appropriate filters. For buildings that are contaminated with microbial-infected material, it is better to discard the contaminated items (carpet, upholstery, ceiling tiles, etc.) rather than to attempt to disinfect them; however, if the extent of contamination is limited or uncertain, disinfection may be attempted using high-efficiency particulate air (HEPA) filters. These filters are introduced into the airstream immediately before it enters the space so that any contaminants generated within the system itself are also caught (**Figure 5**). Since it is almost impossible to clean contaminated suspended ceiling-return air plenums, these may have to be by-passed by installation of return air ductwork. During building clean-up, microbially laden materials should be carefully removed so as to minimize aerosolization of inhalable particulates.

The selection of filters varies according to initial and maintenance costs, energy costs and perceived levels of "quality" required for a building space. Generally, as air filtration efficiency

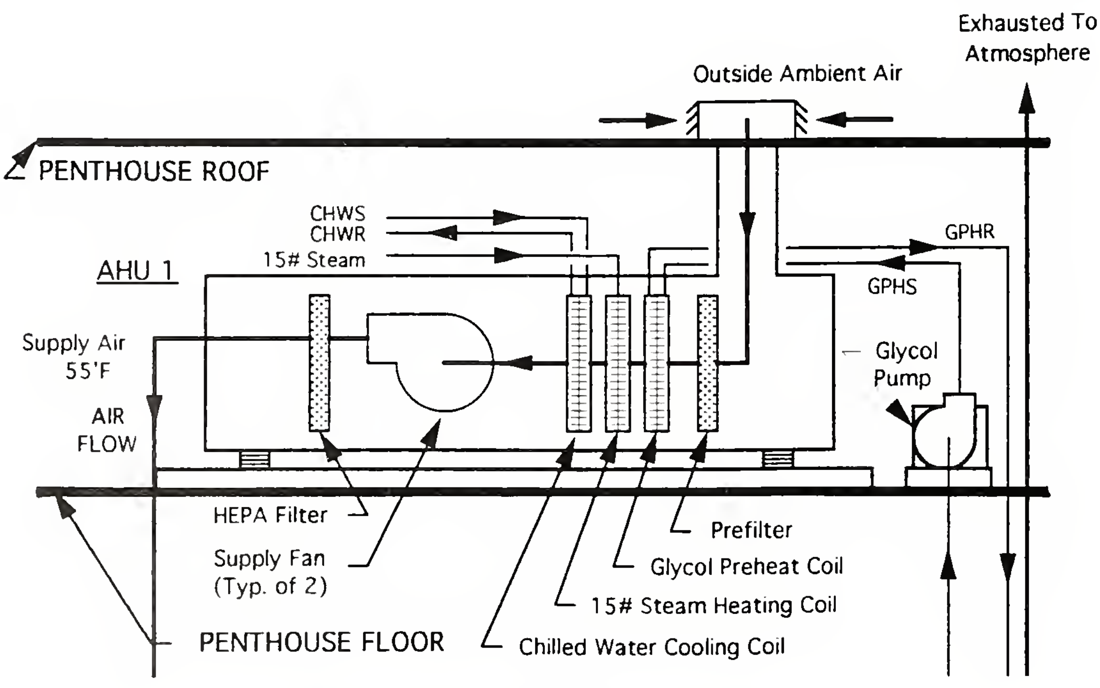


Figure 5. Location of HEPA filter in an air handling unit.

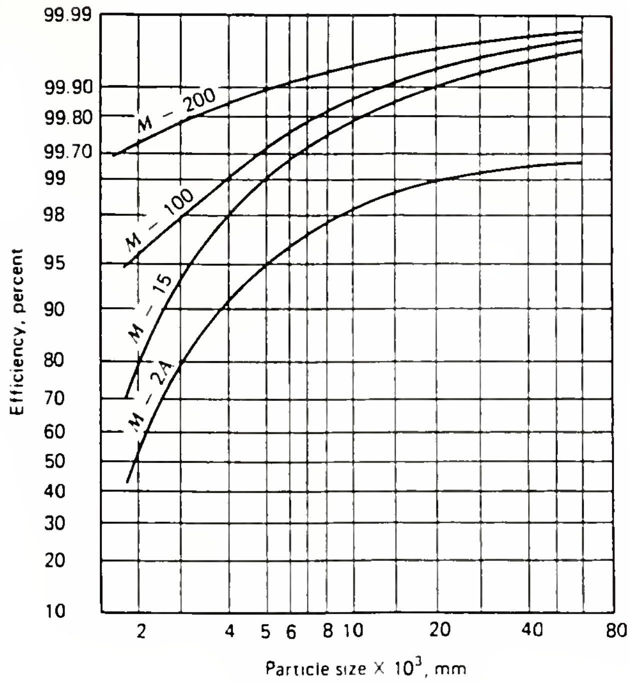


Figure 6. Efficiency of high-performance dry-media filters

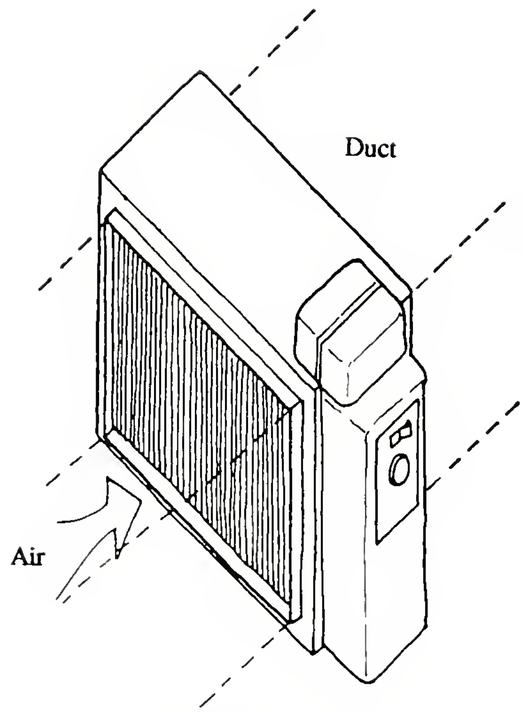
increases, the initial cost of the filter increases, and the air pressure drop across the filter increases. An increase in air pressure drop results in an increase in the required fan power and, thus, an increase in operating cost. **Figure 6** and **Table 2** show the efficiency of different high performance filters as function of particle size.

One type of air cleaning device—the electrostatic air cleaner—has both reasonable efficiency and a low pressure drop, although the initial cost is high. In this device, air is drawn through an electrostatic field in which particles in the air take on an electrostatic charge and are attracted to electrostatically charged plates where they are collected **(Figure 7)**. An advantage of these types of air cleaners is that they are effective even on very small particles. One drawback of these devices, however, is the generation of small quantities of ozone which may present a health hazard. Another disadvantage is that as the build-up of dust assembles on the charged plates, globules of charged dust sometimes spall off and continue downstream until

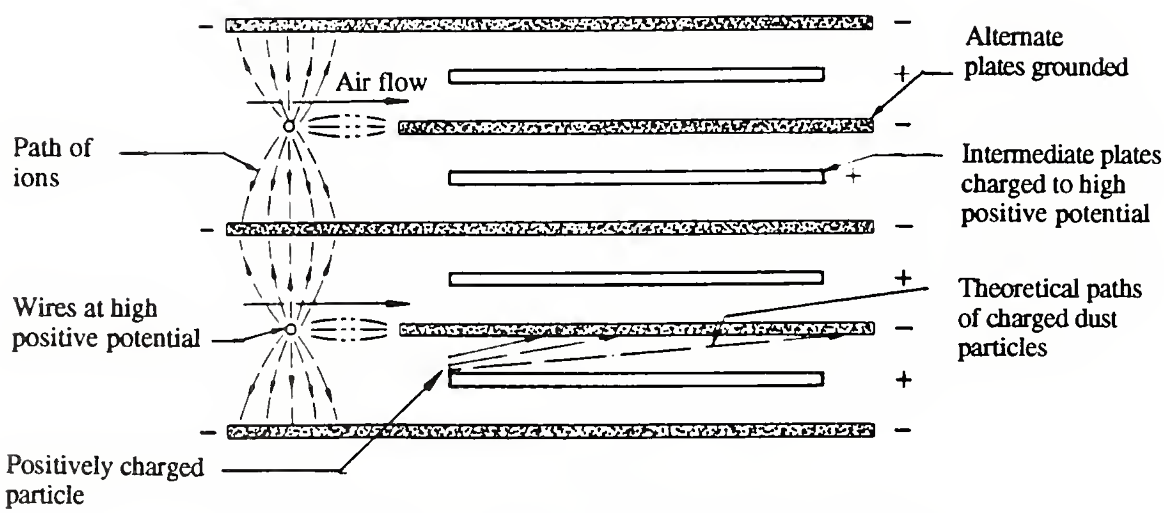
Table 2. Engineering Data of High Performance Dry-Media Filters
(corresponding to Figure 6)

	Dimension (inch)				
	12*24*8	12*24*12	24*24*8	24*24*12	
Media Type	**Rated Capacity (ft^3/min)**				**Pressure Loss (in. H_2O)**
M-2A	900	1025	1725	2000	0.15
M-15	900	1025	1725	2000	0.35
M-100	650	875	1325	1700	0.40
M-200	450	630	920	1200	0.40
	Effective Filtering Area (ft^2)				
	14.5	**20.8**	**29.0**	**41.7)**	

Note: 1 in. = 25.4 mm; 1 in.^{2} = 645.2 mm^2; 1 ft^3/min = 0.472 l/s; 1 ft^2 = 0.0929 m^2; 1 in. H_2O = 248.8 Pa



(a) Air cleaner inserted in duct



(b) Detail showing components and charging mechanism

Figure 7. Electrostatic air cleaner

caught by the cooling coils or the dust is distributed to the occupied space. If this happens on a large scale, a considerable build-up of space charge will result, which not only drives the charged dust particles to the wall and causes blackening of the surface, but it may represent a certain health hazard to space occupants. Electrostatic filters can be automatically washed to eliminate spall-off, but there is no assurance that spalling will not occur in between washing cycles.

Instead of integrating expensive high-efficiency filtering systems with the central HVAC unit, another alternative would be the zoning of stand-alone air filtering equipment operating independently of the central HVAC system to achieve both a high circulation rate and proper air mixing. No ductwork is required. Thus, each zone's filtering system has its own fan, which can operate either with or without the central HVAC fan. Air circulation through these filters should occur at rates between 6 and 10 space air changes per hour.

Design properly maintainable mechanical systems and spaces. A frequent cause of microbial contamination is poor engineering design of the system leading to difficulties in getting access to certain components of the HVAC system. The following examples illustrate such cases:

- AHUs are designed without access doors to the heat exchanger section.
- Small AHUs and heat pumps are located in inaccessible spaces above ceiling tiles prohibiting entry into mechanical components to clean coils, drain pans, etc.
- Some mechanical rooms and plenums are so confining that access is rendered difficult if not impossible once the equipment is installed. Architects must be made to provide adequate space when buildings are designed or remodeled.

In addition to remedying the above, fan coil unit designs should facilitate exposure of drain pans, coils, etc., as quickly as possible. **Figure 8** illustrates the configuration of equipment of a generic HVAC system for a building experiencing VOCs, airborne infectious diseases and chemical and particulate contamination. The "worst-case scenario" is not likely to occur except in severe cases of contamination. A high level of radiation can be emitted from ultra-violet (UV) lamps, located in the AHU adjacent to the carbon canisters, and it is vitally important to interlock the lamps with the access door latch and the fan motor to prevent eye injury to operating engineers. While the cost of such a system may be high, it will most likely be lower than the cost of decontaminating an infected building. Moreover, for new construction, is it prudent to invest in an on-line decontamination system up front or take the chance that the building will escape the fate of many? Once a building is contaminated, remedial actions can be extremely expensive and the loss of tenants (as well as reputation) is sometimes unrecoverable.

CONCLUSION

The major contamination experienced by most HVAC systems is microbial in the form of a bioaerosol. Since most bacteria and fungi are facultative parasites and grow on both living and nonliving organic material, it is possible for an air-conditioning system to act as an amplifier or disseminator. This applies especially to saprophytic microorganisms, fungi, protozoa and most bacteria. With the exception of *Legionella* which must reside in a water droplet, if the substrate hosting the organism is disturbed, the organism becomes airborne. Thus, the air-conditioning system becomes an accomplice in bacterial dissemination.

While we have little control of the external environment, we *can* do something about the indoor environment. Remediation can be in the form of a clean-up (after contamination is discovered) or on-line which assigns remediation to the air-conditioning system *while it is operating*. A manual clean-up would mean the air-conditioning system would be deactivated for a period of time while the cleaning and disinfection is done. Should the role of the air-conditioning system be expanded to include air quality control? If so, definition of the new design parameters for such air-conditioning systems should be assigned and adopted by ACGIH, ASHRAE, BOCA and others, as recommendations, standards or code requirements.

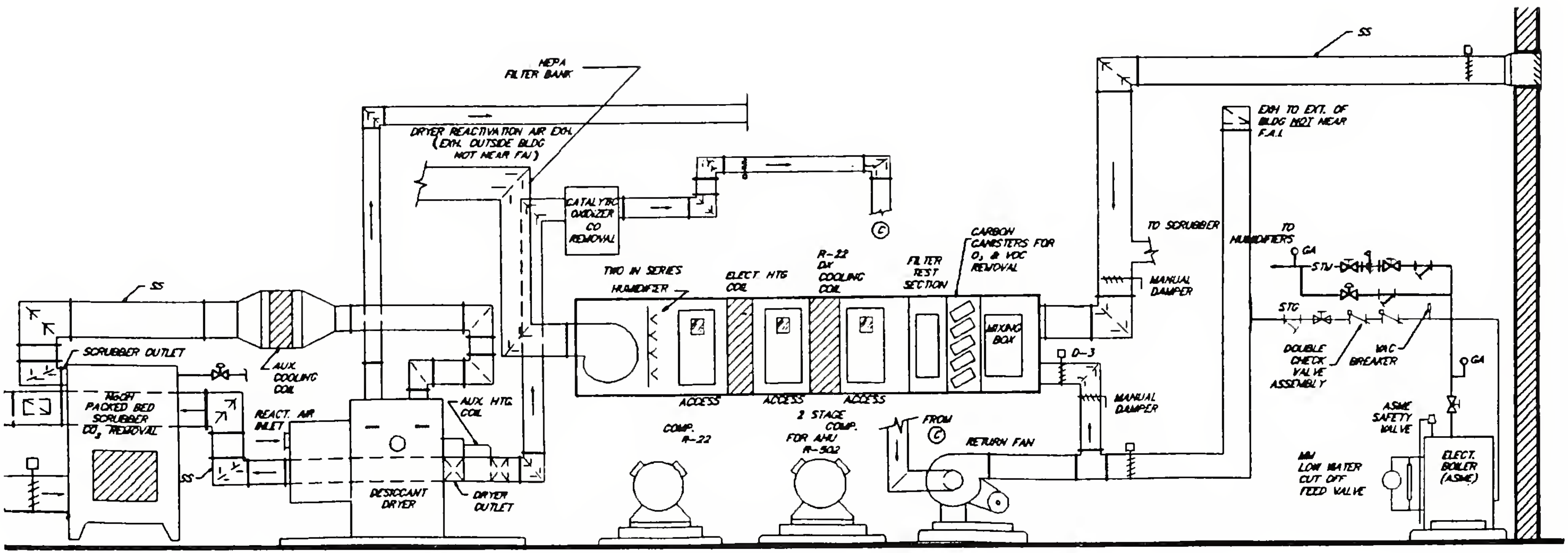


Figure 8. Schematic diagram of the configuration of equipment of a generic HVAC system (designed to keep a building free of chemical, microbial and particulate contamination)

The following list specifies equipment and performance of a generic HVAC/IAQ system to detect and remove bacterial contamination of all types. Design parameters for the new or retrofit, on-line air quality control system would include:

- Conformance during the commissioning process with recommended microbial exposure range limits. Based on the cited literature, the upper limit should not exceed 1000 CFU/m^3. Reference is also made to the ACGIH (1989) guidelines recommending comparison of indoor and outdoor concentrations.

- Airborne hypersensitivity disease detection.

- Biocidal treatment of the air stream while diverting the discharge air outside the building, and expiration by UV lamps of certain other active bioaerosols.

- Depyrogenation cycles through the AHU at 540°F (280°C) while diverting the air outside (filters should be removed during this cycle to prevent damage).

- New standards for equipment manufacture to include materials and assembly. AHUs and ductwork should not have insulation on the inside surface which can collect and amplify microorgansims; inside duct surface should be smooth such as aluminum or stainless steel; water atomization humidifiers should not be used (steam only); all equipment designed for high temperature depyrogenation if this cycle is included; ducts should have flanged joints; gaskets and sealants should not contain organic or VOC pollutants.

- A microbial sensing system can possibly be installed to detect a build-up in concentration passing through the AHU. The bacterial colony morphology should be established at generic level (*Bacillus, Strepococcus, Micrococcus and Corynebacterium*) for comparison with test samples.

- As previously stated, ductwork should not be installed below ground, if possible. Existing underground ducts should be removed or filled with a strong biocide and sand combination and sealed with a thick concrete topping layer, caulked and sealed at the edges. New return ducts should be installed for existing systems. (If ceiling diffusers are used, use low sidewall return registers).

- Buildings should have positive pressure with respect to the outside.

- A bake-out cycle could possibly be designed to provide 100 to 105°F (38 to 41°C) air throughout the building to drive off VOCs and reduce bioaerosols. The bake-out equipment should include two run-around coils, piping and a small pump to reduce operating costs. The initial bake-out should occur after the building is completed and before occupancy. Only 100 percent outside air should be used, and this air should be entirely exhausted. The high temperature air should not be continuously circulated throughout the building, but should take advantage of thermal "pumping" characteristics to induce VOC release from fungi and building materials, i.e., 2 hours at 105°F (41°C), 3 hours at 80°F (27°C), repeated over a 48 hour period. Continuous 105°F (41°C) air within a building for two days is likely to cause extensive damage to the building such as warping of doors, wrinkling of carpeting, possible fracture of windows and thermal expansion of various components. The building should also be brought up to temperature slowly—by 10°F (6°C) increments over a 12 hour preheat period [10°F (6°C) increase every 4 hours].

Other air-conditioning/quality system requirements would, of a necessity, include re-

moval of ozone, VOCs, chemicals and particulates, subjects not part of this discussion. While it is unlikely that all nine requirements would be necessary for any one building, the above parameters can be applied individually as required.

It appears that the building air-conditioning system, which has remained basically unchanged through the years, may become a "building air quality control system." Much research is necessary to determine how we can use building HVAC systems to control the indoor environment, preserve our health, and protect us from sickness generated in the workplace. HVAC systems must function to provide an integrated environment where temperature, air distribution, humidity, energy consumption and IAQ are maintained within acceptable levels.

REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH). 1984. Evaluating office environmental problems. *Annals. American Conference of Governmental Industrial Hygienists.* 10:1-136.

American Conference of Governmental Industrial Hygienists (ACGIH). 1989. *Guidelines for the assessment of bioaerosols in the indoor environment.* Cincinnati, OH: ACGIH.

Arnow, P., J. Fink, D. Schlueter, J. Barboriak, G. Mallison, S. Said, S. Martin, G. Unger, G. Scanlon, and V. Kurup. 1978. Early detection of hypersensitivity pneumonitis in office workers. *American Journal of Medicine.* 64:234-42.

Brundrett, G.W., and A.H.S. Onions. 1980. Molds in the home. *Journal of Consumer Studies and Home Economics.* 4:311-21.

Bourdillon, R.B., O.M. Lidwell, J.E. Lovelock, and W.F. Raymond. 1948. Airborne bacteria found in factories and other places: Suggested limits of bacterial contamination. *Studies in Air Hygiene.* Medical Res. Coun. Spec. Rep. Series No. 262. London: HM Stationary Office, 257-63.

Burge, H. 1990. Bioaerosols: Prevalence and health effects in the indoor environment. *Journal of Allergy and Clinical Immunology.* 86(5):687-701.

Chen, Q., A. Moser, and P. Suter. 1992. A numerical study of indoor air quality and thermal comfort under six kinds of air diffusion. *ASHRAE Transactions.* 98, Pt.1.

Cunningham, G. 1989. Air quality in (N.C. Ruck, ed.) *Building Design and Human Performance.* 29-3. New York: Van Nostrand Reinhold.

Edwards, J.H. 1980. Microbial and immunological investigations and remedial action after an outbreak of humidifier fever. *British Journal Industrial Medicine. 37:55-62.*

EPA. 1989. *Report to Congress on Indoor Air Quality.* Prepared by Indoor Air Division, US Environmental Protection Agency. Washington, DC, August.

Flaherty, D.K., F.H. Deck, J. Cooper, K. Bishop, P.A. Winzenburger, L.R. Smith, L. Bynum, and W.B. Witmer. 1984. Bacterial endotoxin isolated from a water spray air humidification system as a putative agent of occupation-related lung disease. *Infection and Immunity.* 43:206-12.

Fliermans, C., and J. Nygren. 1987. Maintaining cooling systems "free" of Legionella pneumophila, *ASHRAE Transactions.* 93:1405-1415.

Health Directorate Report. 1990. Recommendations for indoor air quality. *Norwegian Public Health Report.* (5/90 - IK 2322). July.

Healthy Buildings International (HBI). 1990. Factors affecting employee health and comfort. *Healthy Buildings.* Nov/Dec.

Healthy Buildings International (HBI). 1991. Contaminant levels compared with normal comfort ranges. *Healthy Buildings.* May/June.

Hirsch, D.J., S.R. Hirsch, and J.H. Kalbleisch. 1978. Effect of central air conditioning and meteorologic factors on indoor spore counts. *Journal of Allergy and Clinical Immunology. 62:22-26.*

Hodgson, M.J., and C.A. Hess. 1992. Doctors, lawyers and building-associated diseases. *ASHRAE Journal.* 34(2): 25-32.

Hodgson, M.J., P.R. Morey, M. Attfield, W.G. Sorenson, J.N.Fink, W.W. Rhodes, and G.V. Visvesvara. 1985. Pulmonary disease associated with cafeteria flooding. *Archives of Environmental Health.* 40:96-101.

Kozak, P.P., G. Gallup, L.H. Cummins, and S.A. Gillman. 1978. Factors of importance in determining the prevalence of indoor molds. *Journal of Allergy and Clinical Immunology. 27(6):1001.*

Kozak, P.P., G. Gallup, L.H. Cummins, and S.A. Gillman. 1980. Currently available methods for home mold surveys.II. Examples of problem homes surveyed. *Annals of Allergy.* 45:167-76.

Medical Research Council (MRC) Symposium. 1977. Humidifier fever. *Thorax.* 32:653-63.

Mendell, M., and A. Smith. 1990. Consistent pattern of elevated symptoms in air-conditioned office buildings: A reanalysis of epidemiologic studies. *American Journal of Public Health.* 80:1193-1199.

Miller, J.D., P. Laflamme, A.M. Sobol, Y. Lafontaine, and Greenhalgh. 1988. Fungi and fungi products in some Canadian houses. *International Biodeterioration.* (As reported in Walkinshaw, D.S. 1988.

Canadian Indoor Air Quality Standards, Guidelines and Research Activities. *In Indoor and Ambient Air Quality. R. Perry and P.W. Kirk eds. Selper Ltd., London).*

Morey, P.R. 1988a. Experience on the contribution of structure to environmental pollution. *Architectural Design and Indoor Microbial Pollution.* ed. R.B. Kundsin. New York: Oxford University Press. 40-80.

Morey, P.R. 1988b. Microorganisms in buildings and HVAC systems: A summary of 21 environmental studies. *Engineering Solutions to Indoor Air Problems.* Proceedings of the ASHRAE Conference IAQ 88. Atlanta, GA. 10-21.

Morey, P.R., M.J. Hodgson, W.G. Sorenson, G.J. Kullman, W.W. Rhodes, and G.S. Visvesvara. 1984. Environmental studies in moldy office buildings: Biological agents, sources, and preventive measures. *Annals. American Conference of Governmental Industrial Hygienists. 10:21-35.*

Moseley, C. 1990. Indoor air quality problems: A proactive approach for new or renovated buildings. *Journal of Environmental Health.* Nov./Dec.19-22.

Oak Ridge National Laboratory (ORNL). 1985. *Indoor air and human health.* R.B. Gammage and S.V. Kaye, eds. 7th Life Sciences Symposium. Chelsea, MI. Lewis Publishers.

Pope, D.H., and D.M. Dziewulski. 1992. Efficacy of biocides in controlling microbial populations, including Legionella, in cooling systems, *ASHRAE Transcations.* 98: Pt.2.

Pope, D.H., L.W. Eichler, T.F. Coates, J.F. Kramer, and R.J. Soracco. 1984. The effect of ozone on Legionella pneumophila and other bacterial populations in cooling towers. *Current Microbiology.* 10:89-94.

Rose, H.D., and S.R. Hirsch. 1979. Filtering hospital air decreases aspergillus spore counts. *American Review of Respiratory Disease.* 119:511-13.

Scully, R.E., J.J. Galdabini, and B.U. McNeely. 1979. Case records of the Massachusetts General Hospital, Case 47-1979. *New England Journal of Medicine.* 301:1168-74.

Solomon, W.R., H.A. Burge, and J.R. Boise. 1980. Exclusion of particulate allergens by window air conditioners. *Journal of Allergy and Clinical Immunology.* 65:305-8.

Soracco, R.J., H.K. Gill, C.B. Fliermans, and D.H. Pope. 1983. Susceptibility of algae and Legionella pneumophila to cooling tower biocides. *Applied and Environmental Microbiology.* 45:1254-1260.

Soracco, R.J., and D.H. Pope. 1983. Bacteriostatic and bactericidal modes of action of bis(tributyltin)-oxide on Legionella pneumophila. *Applied and Environmental Microbiology.* 45:48-57.

Wallingford, K. 1986. NIOSH field experience overview: Investigating sources of IAQ problems in office buildings. *IAQ '86 Managing Indoor Air for Health and Energy Conservation.* ASHRAE, Atlanta: 448-53.

Wright, T.J., V.W. Greene, and H.J. Paulus. 1969. Viable microorganisms in an urban atmosphere. *Journal. Air Pollution Control Association.* 19:337-41.

Yoshizawa, S., and F. Sugawara. 1985. Standards for airborne bacteria. In *Database of state-of-the-art technology for food bacteria control.* M. Haruta, S. Udagawa, R. Yokayama, eds. Tokyo: Science Forum Co.

Zweiman, B., and A.I. Levinson. 1983. Cell-mediated Immunity. *Allergy, Principles and Practice.* Vol. I, I.E. Middlet, C. Reed, E. Ellis, (eds.), St. Louis: C.V. Mosby.

Multiple Strategies Toward Complex Representations in Building Performance Simulation

Ardeshir Mahdavi and Khee Poh Lam

ABSTRACT

The complexity of comprehensive representations for building performance simulation is illustrated, based on the application of META-4 (mass and energy transfer analysis) in multi-layered building enclosure components. Required multiple modeling strategies (numeric computation, geometric procedures, rule-based approaches, generative and "two-way" systems) are discussed. Frameworks for effective design supporting communicative structures are proposed.

Ardeshir Mahdavi is a Professor and Chair of the Science and Technology Committee in the Department of Architecture at Carnegie Mellon University, Pittsburgh, Pennsylvania. His main areas of research are in building physics, computational building performance simulation and Human Ecology.

Khee Poh Lam is a lecturer in the School of Architecture, National University of Singapore, Republic of Singapore. He teaches Design, Building Construction and Structures and his doctoral research is in the evaluation of hygro-thermal performance of building enclosures through computational simulation.

INTRODUCTION

Continuous advancements in computer technologies have spurred the development of numerous computer aided design tools to assist in performance-based design of buildings. This generally involves the analysis and evaluation of those design features that affect the functionality and occupational quality of a building. However, many of these tools have found limited application in architectural practice. Even then, normally only specialist professionals use these performance simulation models, often for verification purposes; there appear to be three main reasons for this.

First, the tools have, by and large, been developed as stand-alone applications within a specific design domain. The underlying program structure (e.g., process and data management) reflects certain idiosyncratic characteristics that make it difficult for integration with other essential performance evaluation and geometric modeling tools (Mahdavi and Lam 1991). Second, the problem of effective information transfer between the user and the computational environment is still unresolved. Third, efforts in tool development conceptually fall short of challenging the existing (generally sequential and rather fragmented) building delivery process (Mahdavi and Lam 1993).

This paper aims to highlight the complex representations involved in building performance simulation and to discuss various modeling strategies adopted in the META-4 (Mass and Energy Transfer Analysis for multi-layered building enclosure components) computational environment, which include numerical computation, geometric procedures, rule-based approaches, as well as generative and "two-

way" systems. Suggestions for appropriate communicative frameworks are offered.

CRITIQUE OF PARTIAL SPECIFIERS

In the past, the limitations of tools in terms of computational capacity and speed made it necessary to reduce the quantity of information processing for design decision making by introducing "partial specifiers" and rules of thumb. Given the increased computational capabilities in building performance simulation, many of these specifiers and rules should be critically reviewed. For instance, simplified performance indicators such as U-values and Sabine reverberation times are used as exemplification of performance representations ("structures for deriving thermal and acoustical performance") in deriving object-oriented engineering design databases (Eastman et al. 1991).

Aside from the fact that U-value modeling cannot represent transient heat transfer phenomenon, various research studies (Mahdavi 1993)(Mahdavi et al. 1992)(Panzhauser et al. 1990) have demonstrated the limitations of U-value-based calculations for the determination of heat flows, surface temperatures, and critical relative humidities (essential for the evaluation of surface condensation risk) under steady-state conditions. The underlying assumption of U-Value-based calculations is insufficient to deal with many of the complex composite constructions (which involve thermal bridging) and could yield erroneous results in both transmission heat loss and interior surface temperature calculations.

Figure 1 illustrates the point by comparing simulation results of minimum interior surface temperatures using both the detailed numeric method (based on finite difference computation of conductive heat transfer) versus the simplified U-value-based method for 30 planar building components typical of residential constructions in North America (Mahdavi and Mathew 1992). In this case, the simplified method tends to provide over-estimated values in most instances.

In acoustics, notwithstanding the inherent shortcoming of the "classical" notion of reverberation time, the empirical Sabine algorithm for computing reverberation time is also subject to limitations as it is valid only for rooms with low average absorption ($\alpha_m < 0.2$) and, contrary to expectation, it gives reverberation times above zero for $\alpha_m = 1$ **(cp. Figure 2)**.

Similarly, the Sound Reduction Index (R_w) of the building elements (walls, floors) has traditionally been used to specify sound transmis-

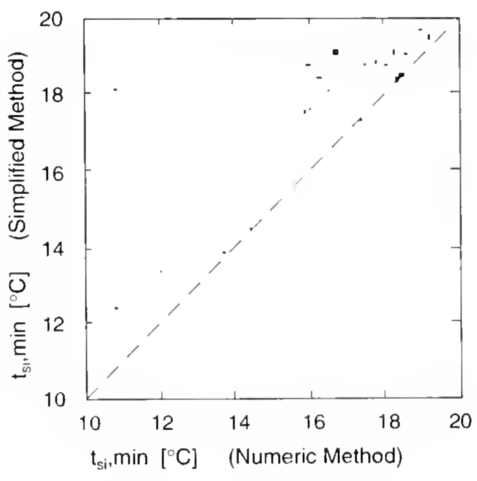


Figure 1. Comparative analysis of indoor surface temperatures for 30 residential constructions using different simulation methods. (Assumed boundary conditions: Outdoor temperature = -15°C, Indoor temperature = 20°C.)

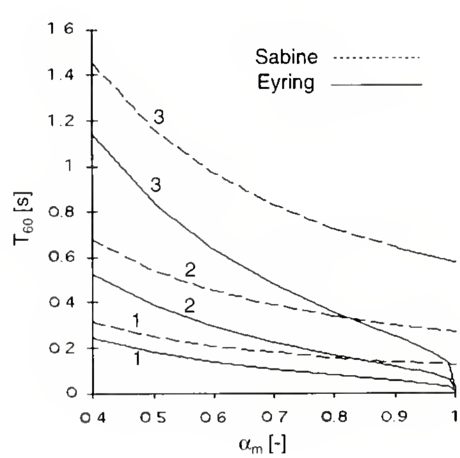


Figure 2. Comparative illustration of reverberation time computation according to Sabine and Eyring for 3 different room configurations with S= total room surface area, V= room volume. [1: S=130 m^2 (1400 ft^2), V=100 m^3 (3532 ft^3); 2: S=600 m^2 (6458 ft^2), V=1000 m^3 (35315 ft^3); 3: S=2800 m^2 (30139 ft^2), V=10000 m^3 (353147 ft^3).]

sion between adjacent spaces. However, the sound transmission is not only a function of the sound insulation of the partition element but also the result of the combined effects of sound transmission through flanking paths (**cp. Figure 3**). Recent documents have identified the normalized sound level difference ($D_{n,T,w}$) as a more appropriate indicator for the formulation of building acoustic requirements (Mahdavi 1991).

A similar configuration to that shown in **Figure 3** is used to demonstrate the potential impact of the flanking transmission on the overall sound level differences (Mahdavi and Lam 1991). **Figure 4** illustrates the deviation of the sound reduction index of the partition element from the normalized sound level difference between two adjacent rooms. The relevant underlying assumptions are summarized in **Table 1** below.

The examples point to the need to recognize and understand the complexities involved in performance evaluation and to derive appropriate frameworks for accommodating and representing these complexities in computer-aided design environments. While it is arguable that particularly in the early design stage a higher level of abstraction is acceptable, it does not mean that rigor and accuracy in the simulation process can be compromised.

Table 1. Matrix of modeling assumptions (cp.Figure 4)

Element	Area $[m^2]$	Surface Density $[kg \cdot m^2]$	Rw [dB]	Junction Geometry [+, T]
Partition Wall	12	100 to 700	38.8 to 66.2	N/A
Exterior Wall	15	400	56.3	T
Interior Wall	15	100	36.8	+
Floor	20	300	52.3	+
Ceiling	20	300	52.3	+

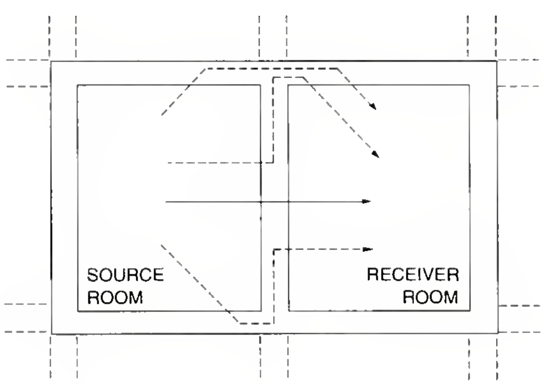


Figure 3. Direct and flanking sound propagation paths between adjacent spaces

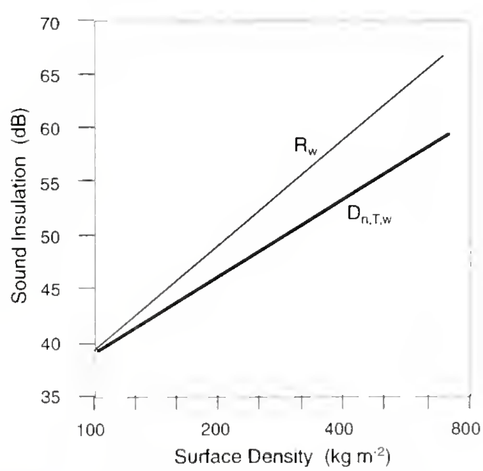


Figure 4. Deviation of the sound level difference between two adjacent rooms in a typical massive construction from the sound reduction index of the partition element as a function of the surface density of the partition element (cp. **Table 1** for modeling assumptions)

MULTIPLE STRATEGIES FOR COMPLEX REPRESENTATIONS

To illustrate the complexity involved, the development of a computational module for simulating and visualizing heat and moisture transfer (META-4) in a multi-layered building enclosure component is presented. This program mainly addresses the need for up-front evaluation of building enclosure components, particularly with respect to their long-term hygro-thermal behavior (Mahdavi and Lam 1993).

As the following sections demonstrate, a rigorous computation of performance-related phenomena may include comprehensive implementation of multiple strategies whereby a variety of approaches such as numeric computation, geometric procedures, rule-based systems, generative and "two-way" routines (Mahdavi and Berberidou-Kallivoka 1992) as well as data management techniques and graphic information representation are utilized simultaneously.

Applicotion of Numeric Methods

Treatment of Boundary Conditions. In establishing the external boundary conditions, it has been common practice to adopt the dry bulb air temperature from the available hourly weather data files. This does not take into account the significant impact of solar radiation on surface temperatures of the building envelope. Weather files generally do not include solar irradiance on arbitrarily oriented surfaces. To obtain these data and to estimate the intensities of direct and diffuse solar radiation on an hourly basis, a solar radiation pre-processor has been incorporated in META-4 (Heindl and Koch 1976).

Based on the radiation intensities, the "radiation air temperature" is then modeled according to Equation 1 (Koch and Pechinger 1977), which can be solved utilizing the Newtonian Approximation Theorem.

$$\alpha_k\,(T_L - T^*) + (a_s \cdot J) + 5.78 \cdot 10^{-8} \cdot \varepsilon_o\,[\,e_u \cdot \varepsilon_u \cdot T_u^4 + (1 - e_u) \cdot \varepsilon_g \cdot T_L^4\,] - [\,5.78 \cdot 10^{-8} \cdot \varepsilon_o \cdot (T^*)^4\,] = 0 \qquad (1)$$

where

a_k = convective heat transmission coefficient in $W{\cdot}m^{-2}{\cdot}K^{-1}$ ($Btu{\cdot}h^{-1}{\cdot}ft^{-2}{\cdot}R^{-1}$)

T_L = outdoor air temperature in K (R)

T^* = radiation air temperature in K (R)

a_s = absorption coefficient of building surface for solar radiation

J = solar radiation intensity in $W{\cdot}m^{-2}$ ($Btu{\cdot}h^{-1}{\cdot}ft^{-2}$)

e_0 = emittance of building surface

e_u = angle factor of surrounding

e_u = emittance of surrounding

e_g = emittance of atmosphere

T_u = surrounding temperature in K (R).

It is also conceivable that internal boundary conditions will also fluctuate depending on occupancy and mechanical system schedules and settings. A procedure has also been incorporated in the program to deal with this scenario.

FD-based Heat Transfer Modeling. The principle governing the heat conduction equation is based on Fourier's Law:

$$q_x = \lambda_{(T,u)} \cdot \left(- \frac{\delta T}{\delta x} \right) \qquad (2)$$

where

q_x = heat transfer rate in the x direction in $W{\cdot}m^{-2}$ ($Btu{\cdot}h^{-1}{\cdot}ft^{-2}$)

$l_{(T,u)}$ = thermal conductivity in $W{\cdot}m^{-1}{\cdot}K^{-1}$ ($Btu{\cdot}h^{-1}{\cdot}ft^{-1}{\cdot}R^{-1}$) for temperature T in K (R) and moisture content u (%).

Under steady-state conditions (with temperature difference ΔT), the temperature distribution within a multi-layered planar building element (with n layers of thickness d_j and conductivity λ_j) can be derived from:

$$q = \left(R_{si} + \sum_{j=1}^{n} d_j \lambda_j + R_{se}\right)^{-1} \cdot \Delta T \qquad (3)$$

where

q = heat transfer rate in $W \cdot m^{-2}$ ($Btu \cdot h^{-1} \cdot ft^{-2}$)

R_{si} = inside surface resistance in $m^2 \cdot K \cdot W^{-1}$ ($ft^{-2} \cdot R \cdot h \cdot Btu^{-1}$)

R_{se} = outside surface resistance in $m^2 \cdot K \cdot W^{-1}$ ($ft^{-2} \cdot R \cdot h \cdot Btu^{-1}$).

As with the limitations of the U-value specifier, the steady-state simulation procedure does not address the dynamic nature of the boundary conditions and its impact on the heat transfer rate. Transient simulation procedures are now regarded as essential for any thermal evaluation. To achieve a higher level of resolution in the hygro-thermal analysis, each material layer of the building component is initially discretized into a predefined number of sublayers. An additional discretization criterion limits the maximum thermal resistance value of each sub-layer so as to maintain the desired computational resolution.

The "effective" surface resistance $R_{se}*$ is calculated as a function of the radiative heat transfer coefficient α_s and the convective heat transfer coefficient α_k:

$$R_{se}^{\ *} = (\alpha_s + \alpha_k)^{-1} \qquad [m^2 \cdot K \cdot W^{-1}] \tag{4}$$

Referring to Equation 1, taking the derivative relative to T^*, the radiative heat transfer coefficient can be determined as follows:

$$\alpha_s = F'(T^*) = -\alpha_k - [5.78 \cdot 10^{-8} \cdot \varepsilon_o \cdot 4 (T^*)^3] \qquad [W \cdot m^{-2} \cdot K^{-1}] \tag{5}$$

The convective heat transfer coefficient α_k is derived as a function of the wind velocity v ($m \cdot s^{-1}$):

$$\alpha_k = 5.9 + 4.1 \cdot v \qquad [W \cdot m^{-2} \cdot K^{-1}] \tag{6}$$

The "effective" $U*$-value of the enclosure component is then given by:

$$U^* = (R_{si} + \sum_{j=1}^{n} d_j \lambda_j + R_{se}^{\ *})^{-1} \qquad [W \cdot m^{-2} \cdot K^{-1}] \tag{7}$$

The calculation of transient temperature distribution in the sub-layers is based on the substitution of the transport equation by finite differences and the corresponding balance equations are substituted by finite control volumes and solved by the tri-diagonal matrix solution technique. Latent heat exchange associated with condensation of water vapor or evaporation of moisture in the component sublayers is accounted for in the procedure and expressed as a heat source or heat sink term in the finite control volume formulation.

Dynamic Modification of Thermal Conductivity. A procedure has been implemented to dynamically model the effect of moisture content on the thermal conductivity of the materials (Sigmund 1984)(Wiese 1985). The thermal conductivity (λ) for the material with a given moisture content (u) can be derived from the thermal conductivity of the material (λ_{def}) with the "default" moisture content (u_{def}):

$$\lambda = \lambda_{def} \cdot (1 + Z) \cdot (1 + Z_{def})^{-1} \qquad [W \cdot m^{-1} \cdot K^{-1}] \tag{8}$$

In this equation, Z is the thermal conductivity incremental factor related to the moisture content of the material. Z_{def} refers to the incremental factor at default moisture content, which is a statistically defined value below which 90% of the empirical measurement results lie (Gösele and Schüle 1983). Volume and mass-related default moisture content for various common building materials can be obtained from DIN 1981. Examples of values for Z_{def} are given in ÖNORM 1989.

Computation of Water Vapor Diffusion. For the calculation of water vapor diffusion, the material property μ (water vapor diffusion resistance index) of the component layers must be known (CEN 1991). As a dimensionless specifier, μ indicates how much greater the water vapor diffusion resistance of the material is than that of an equally thick layer of stationary air at the same temperature. Given the μ values,

Table 2. Procedure for calculating angle α

Condition	$\alpha =$
$p_{s,j} > p$	$\arctan\ [\sum_{j=1}^{m} \mu_j \cdot d_j / (p_{s,j} - p)]$
$p_s = p$	90
$p_{s,j} < p$	$180 - \arctan\ [\sum_{j=1}^{m} \mu_j \cdot d_j / (p - p_{s,j})]$

the "actual" water vapor pressure distribution can be obtained using the following equation:

$$g = [\ (\frac{1}{\beta})_i + 1.5 \cdot 10^6 \cdot \sum_{j=1}^{n} \mu_j d_j + (\frac{1}{\beta})_e\ ] \cdot \Delta p \qquad (9)$$

where

g = water vapor diffusion density in $kg{\cdot}m^{-2}{\cdot}h^{-1}$ ($lb{\cdot}ft^{-2}{\cdot}h^{-1}$).

Δp = total vapor pressure differential between outdoor and indoor in Pa (psi)

μ_j = diffusion resistance coefficient of sub-layer j

$(1/\beta)_e$, $(1/\beta)_i$ = external and internal surface diffusion resistance in $m^2{\cdot}h{\cdot}Pa{\cdot}kg^{-1}$ ($ft^{-2}{\cdot}h{\cdot}psi{\cdot}lb^{-1}$).

For the internal surface diffusion resistance $(1/\beta)_i$, a constant value 8300 $m^2{\cdot}h{\cdot}Pa{\cdot}kg^{-1}$ (5.403 $ft^2{\cdot}h{\cdot}psi{\cdot}lb^{-1}$) for air temperatures between 10 and 20°C (50 and 68°F) and temperature difference between air and wall of 5 to 10 K (9 to 18R) is used. The values for the external surface diffusion resistance $(1/\beta)_e$ are dependent on wind velocity. The following approximation for the temperature range of -20 .. 30°C (-4 .. 86°F) and wind velocity (v) range of 1 .. 20 $m{\cdot}s^{-1}$ (197 .. 3937 $ft{\cdot}min^{-1}$) is implemented:

$$(\frac{1}{\beta})_e = 100\ [36 - (120 + 60v - v^2)^{0.5}]$$

$$[m^2{\cdot}h{\cdot}Pa{\cdot}kg^{-1}] \qquad (10)$$

The overall vapor pressure gradient Δp can be calculated using relative humidities (RH_i , RH_e) and saturation pressures inside and outside ($p_{s,i}$, $p_{s,e}$):

$$\Delta p = (RH_i \cdot p_{s,i}) - (RH_e \cdot p_{s,e}) \qquad (11)$$

Application of Geometric Procedures to Determine Condensation Layer / Zone

To achieve a dynamic visualization of the diffusion process, it is necessary to obtain rapidly the "true" curve of water vapor pressure. This curve is determined by adopting a "tangent" procedure (Mahdavi and Lam 1993) formulated as a generalized solution for the graphic Glaser method (Glaser 1959). This procedure employs a geometric method for detecting condensation layers and zones within the building component. Given the water vapor pressure p and saturation curve, an angle α is calculated according to **Table 2. Figure 5** shows a magnified portion of an exemplary building component to illustrate this procedure. The angle α is calculated sequentially at each time step for all component sub-layers.

Any reversal in the trend of α (from ascending to descending or vice versa) during this mapping process indicates the start or end of a condensation zone. A recursive application of this tangent procedure identifies the extent of condensation layers and zones. Within the condensation zone the "true" vapor pressure values are assumed to be identical to the corresponding saturation pressures.

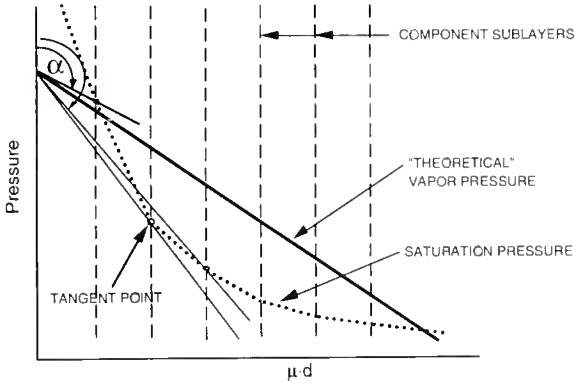


Figure 5. Tangent method for determining "true" vapor diffusion path and condensation layers and zones

Application of Heuristic Rules to Moisture Distribution

Having identified the condensation layer(s) or zone(s), the condensate amount can be computed. In the case of the "block" procedure, long-term steady-state periods are defined for the process of condensation and drying. A dynamic simulation approach is likely to provide a more accurate representation of the fluctuation in moisture content on a shorter time scale. The quantity of condensation (g_c) at a certain sub-layer m of a building component with n sub-layers is calculated using the following equation:

$$g_c = (p_i - p_m) \cdot \left(1.5 \cdot 10^6 \cdot \sum_{j=1}^{m} \mu_j d_j\right)^{-1} - (p_m - p_e) \cdot \left(1.5 \cdot 10^6 \cdot \sum_{j=m+1}^{n} \mu_j d_j\right)^{-1} \tag{12}$$

where

g_c = quantity of condensation in kg·m^{-2}·h^{-1} (lb·ft^{-2}·h^{-1})

p_i = internal water vapor pressure in Pa (psi)

p_e = external water vapor pressure in Pa (psi)

p_m = water vapor (saturation) pressure at layer m in Pa (psi).

The amount of water (g_d) drying out of the condensation layer m is given by:

$$g_d = (p_s - p_i) \cdot \left(1.5 \cdot 10^6 \cdot \sum_{j=1}^{m} \mu_j d_j\right)^{-1} + (p_s - p_e) \cdot \left(1.5 \cdot 10^6 \cdot \sum_{j=m+1}^{n} \mu_j d_j\right)^{-1} \tag{13}$$

where

g_d = amount of water drying out of condensation layer in kg·m^{-2}·h^{-1} (lb·ft^{-2}·h^{-1})

p_s = water vapor saturation pressure at the condensation layer in Pa (psi).

A procedure currently implemented in META-4 is based on "heuristic" description of the change in the mass transfer mechanism as a result of phase change and the effective distribution mode within the sub-layers of the component. It is adapted from the theoretical assumptions used in the GLASTA program (Standaert 1988). However, the discretization of material layers in META-4 provides an improved resolution of the simulation results. The rule-based prediction of the extent of the humidification of the sub-layers (L_i) is based on the definition of the critical water content of a material ($\rho_{w,c}$). The process is then controlled according to the following set of rules:

1. ***if*** ($\rho_{w,i} < \rho_{w,c,i}$)
2. ***then*** water vapor diffusion computation;
3. ***else if*** L_{i+1} capillary
4. ***then*** transport ($\rho_{w,c,i} - \rho_{w,i}$) to L_{i+1} {"cold side" sub-layer}
5. ***else*** {$L_{i+1} \equiv$ non-capillary}
6. transport ($\rho_{w,c,i} - \rho_{w,i}$) to L_{i-1} {"warm side" sub-layer}.

Statement 2 refers to the mass transfer by diffusion. Statements 3 to 6 refer to mass transfer in the liquid phase. Similar rules are implemented to simulate the drying-out cycle.

Generative Routines

Although the existing structure of META-4 follows the conventional "one-way" sequence of design to performance transformation, it has a clear potential for adaptation of "two-way" feedback procedures (Mahdavi 1993)(Mahdavi and Berberidou-Kallivoka 1992). To demonstrate this point, the simple (steady-state) condensa-

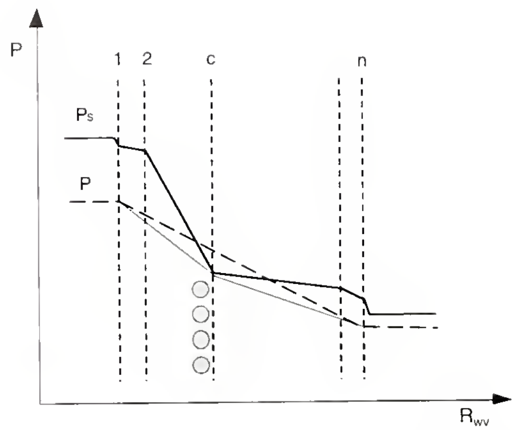


Figure 6. Simple typical condensation case within a multi-layered building component

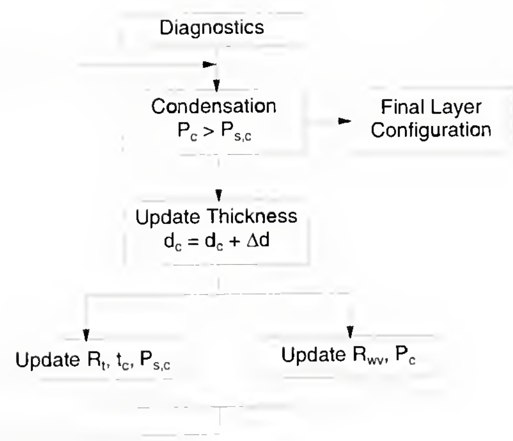


Figure 7. Diagnostic process of generative modification of layer structure

tion case within a multi-layered building component is considered here **(cp. Figure 6)**.

It is desirable to accommodate routines that are activated after diagnostics (e.g. detection of condensation by the tangent procedure) to generate alternative designs that would avoid condensation. A related strategy is described below for the simple case illustrated in **Figure 6.**

Per definition, condensation occurs at layer interface c if the computed theoretical vapor pressure p_c is higher than the respective saturation pressure $p_{s,c}$, that is,

$$p_c > p_{s,c} \tag{14}$$

An increase in the thickness of the layer before the condensation interface d_c has a twofold effect on the reduction of the condensation probability. The additional thickness and the corresponding increase in the thermal resistance R_t leads to a higher temperature t_c at interface c and thus to a higher saturation pressure $p_{s,c}$ since

$$p_{s,c} = f(t_c) \tag{15}$$

The additional thickness also increases the vapor diffusion resistance ($R_{wv} = \mu d$), which in turn results in a lower P_c value:

$$p_c = p_i - [\sum \mu d_{(1\rightarrow c)} \cdot (\sum \mu d)^{-1}_{(1\rightarrow n)}] \tag{16}$$

Figure 7 illustrates this process of generative modification of the layer structure. Of course, this procedure must be extended and modified to control the logical consistency of the resulting thickness and accommodate the recursive treatment of the thickness of other layers if necessary. The modification should also address the problem of introducing new layers (e.g., vapor retarders), multiple condensation zones and dynamic simulation mode. Despite all these limitations, this process exemplifies the strategic potential of generative and "two-way" approaches toward enhancement of the design support capabilities of META-4.

COMMUNICATION FRAMEWORKS

The computational features of META-4 described above provide the potential for performing complex modeling and evaluation operations. However, this potential must be effectively communicated to the user if a more pervasive use of the tool is to be expected. The communicative framework of the design support environment (for information exchange both in terms of input as well as the provision of feedback to the user) should realistically consider the information-processing capacity/characteristics of the users (mainly practitioners), while maintaining sufficient flexibility within the modeling environment to allow for the evaluation of various design options.

A review of the literature on man-machine interface design suggests that two vital principles need to be considered, namely, consistency

and user-centered design, particularly in reference to the importance of the "task domain" and of making the "mechanisms of the system match the thought and goals of the user" (Hutchins et al. 1985). In the development of the META-4 computational environment, careful consideration was given to the establishment of an effective graphic interface for structuring data input and visualization of the hygro-thermal process. Building performance simulation requires substantial input data in terms of material properties and configuration, dynamic external environmental conditions and the desired internal environmental conditions to satisfy functional requirements and comfort criteria. In META-4, a comprehensive single-screen graphic input format has been developed **(cp. Figure 8 and Figure 9)** for both the steady-state and the transient simulation modes. It allows the user to immediately gain an overview of the design parameters and data input requirements that are supported by relevant built-in libraries. Inherent in this approach is the assurance of data acceptability (type matching) and dimensional accuracy. The graphic interface is designed to efficiently facilitate the management and processing of data relevant to the application.

Material specification and the configuration of any arbitrary multi-layered building enclosure component is supported by a built-in material library. In the building industry, new materials are continuously being introduced. Therefore, it is necessary for the library of materials to be customizable and upgradable **(cp. Figure 10)**. This spread sheet input format allows for future inclusion of categorical properties for each material that would be required for other building performance simulation, such as acoustics and lighting. Retrieval of previously created construction files is also facilitated **(cp. Figure 11)**.

The result output interface tracks the "real-time" simulation process and presents the results numerically and/or graphically to the user. The benefit of the graphic output is to enable the user to observe critical conditions that may arise during the simulation period. The graphical representation of temperature, water vapor and moisture distribution within the enclosure component sub-layers provides an effective representation of the pattern of behavior of the component as the boundary conditions vary in time **(cp. Figure 12)**. The ability to conduct parametric simulation studies and observe the response patterns graphically promises to be particularly effective from a pedagogical point of view.

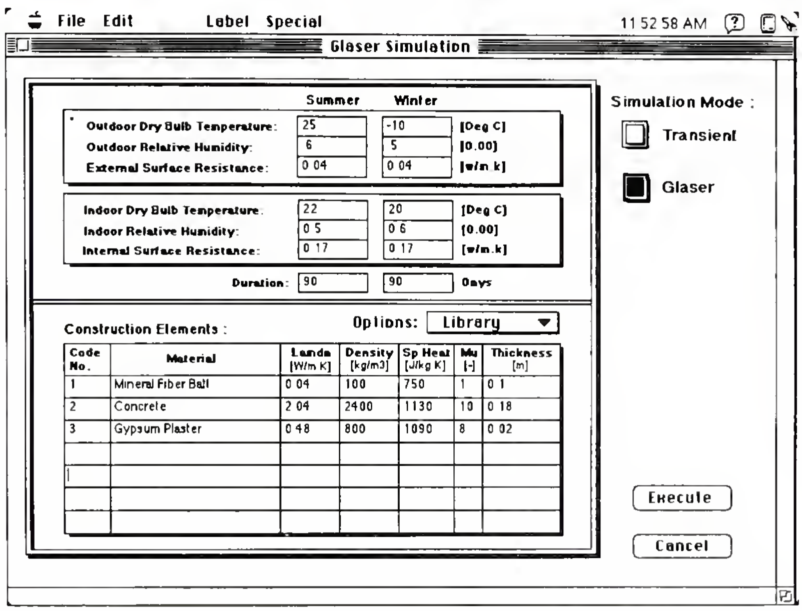


Figure 8. Single-screen data input format for the steady-state (Glaser) simulation mode

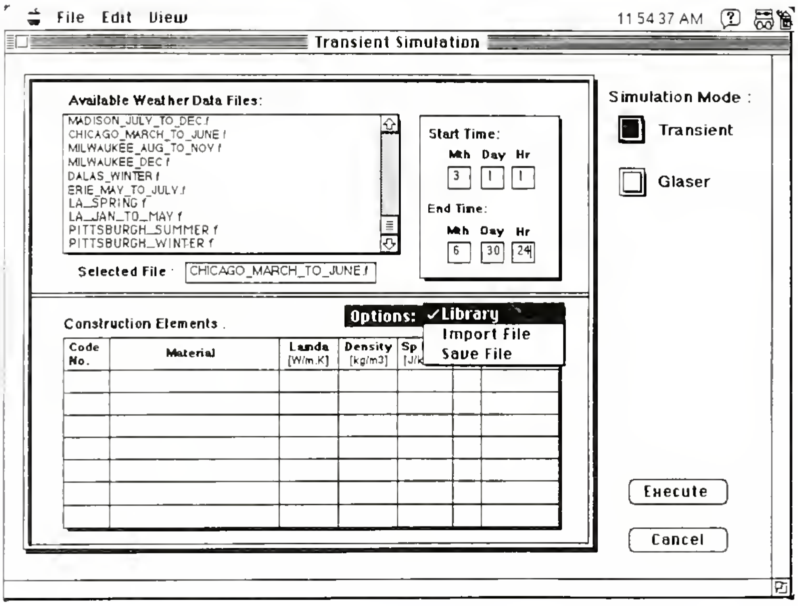


Figure 9. Single-screen data input format for the transient simulation mode with weather data file and schedule selection

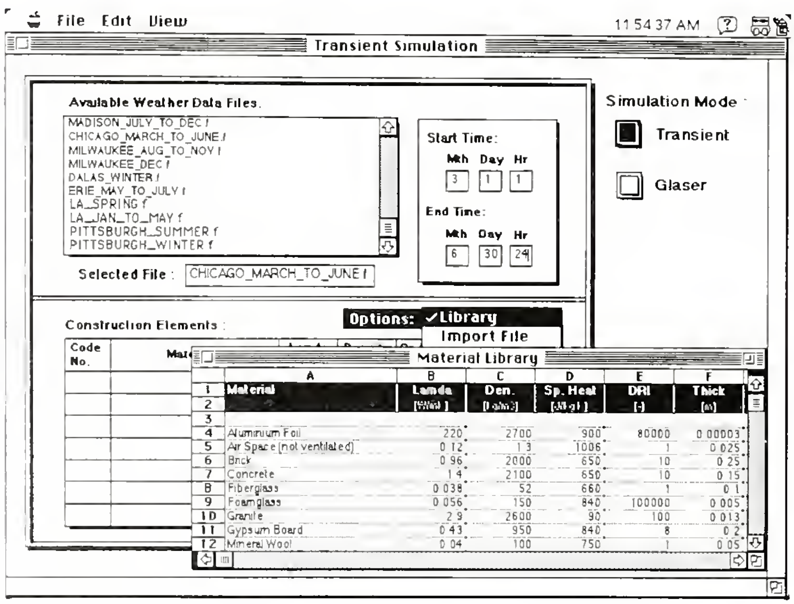


Figure 10. Material specification and configuration supported by a library of materials presented in a spread sheet style format to facilitate customization and upgrade

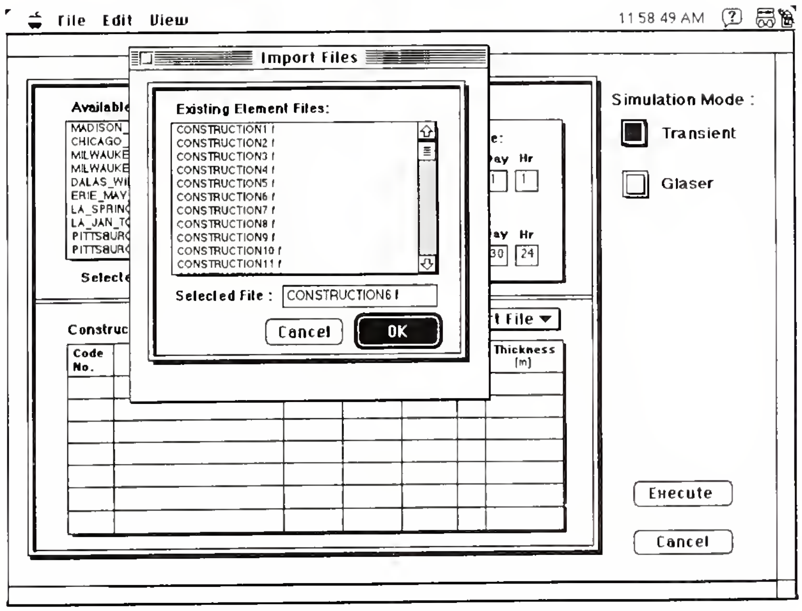


Figure 11. Retrieval of existing construction files is facilitated

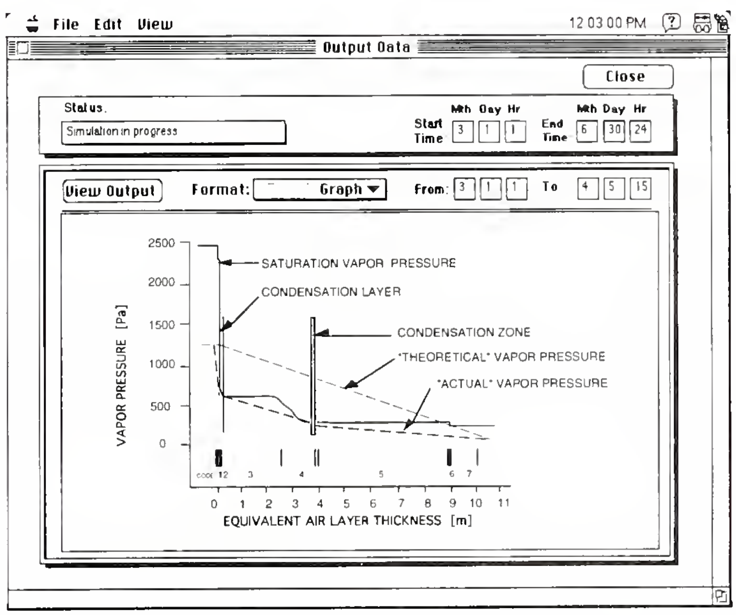


Figure 12. Example of a graphic output window illustrating saturation and "true" vapor pressure curves as well as condensation layers and zones.
(Component layers: 1. Gypsum Drywall, 2. Fiberglass, 3. Aluminum Foil, 4. Polyurethane Foam Board, 5. Building Paper, 6. Air Space (non-vent.), 7. Granite.)

CONCLUSION

The current state of performance representation in computer-aided architectural design environments is characterized by a dilemma between the two-fold requirement of rigorous modeling capabilities (crucial for supporting competent design decision making) and integration (essential for supporting participatory approaches to design through effective communicative structures). An original effort in developing the META-4 simulation environment has been introduced to illustrate the importance of both rigorous performance representation and effective communicative structures. Preliminary experimental application of the program within the personal computer domain has yielded encouraging results toward meeting the objectives set forth in this research effort.

REFERENCES

CEN. 1991. Thermal insulating products for building applications - Determination of water vapor transmission properties. *European Standard*, Draft pr EN, CEN TC88 WG1N448.

DIN. 1981. DIN 4108 *Wärmeschutz im hochbau*. Teil 4. Wärme-und feuchteschutztechnische Kennwerte, Ausgabe (Heat insulation in buildings. Part 4. Specification for heat and moisture treatment).

Eastman, C. M., A. H. Bond, and S. C. Chase. 1991. A data model for engineering design databases. EDM - A data model for engineering product databases. *research report no. 10*, Department of Architecture, University of California, Los Angeles.

Glaser, H. 1959. Graphisches verfahren zur untersuchung von diffusionsvorgängen (Graphical procedures for the investigation of diffusion phenomenon) *Kältetechnik* 11, Heft 10, 345-349.

Gösele, K., and W. Schüle. 1983. Schall, Wärme, Feuchte (Sound, Heat, Moisture). *Bauverlag GmbH*, Wiesbaden und Berlin, 205-258.

Heindl, W., and H. A. Koch. 1976. Die berechnung von sonneneinstrahlungsintensitäten für wärmetechnische untersuchungen im bauwesen (The calculation of solar radiation intensities for thermal studies in buildings). *Gesundheits-Ingenieur* 97, H.12, 301- 314.

Hutchins, E. L., J. D. Hollan, and D. A. Norman. 1985. Direct manipulation interfaces. *Human-Computer Interaction* 1, 311-338.

Koch, H.A., and U. Pechinger. 1977. Möglichkeiten zur berücksichtigung von sonnen-und wärmestrahlungseinflüssen auf gebäudeoberflächen (Possibility of consideration of solar and thermal radiation impact on building surfaces). *Gesundheits-Ingenieur* 98, H.10, 265-280.

Mahdavi, A. 1991. Sound transmission between rooms: a comparative analysis of calculation methods. *Journal of Acoustical Society of America*, Vol. 90, Pt. 1, 927-936.

Mahdavi, A. 1993. Computational frameworks for numeric assessment of steady-state conductive heat transfer through thermal bridges. *ASHRAE Transactions*, Vol. 99, Pt.1, 301-307.

Mahdavi, A., and L. Berberidou-Kallivoka. 1992. *A 'two-way' inference approach to daylighting simulation*. IESNA Annual Conference, San Diego, CA. Technical Papers, 263-271.

Mahdavi, A., T. Jeung, and P. Mathew. 1992. Conductive heat transfer through insulated building enclosure components: a cross-sectional analysis of constructions typical to low-rise residential and commercial buildings in North America. *Journal of Thermal Insulation and Building Envelope*, Vol. 16, 161-182.

Mahdavi, A., and K. P. Lam. 1991. Performance simulation as a front-end tool for integrative conceptual design evaluation. *Proceedings of the 2nd World Congress on Technology Improving the Energy Use*, Comfort and Economics of Buildings, Nice, France. Ed. J.A. Clarke, J.W. Mitchell, and R.C. Van de Perre. The International Building Performance Simulation Association.

Mahdavi, A. and K. P. Lam. 1993. Dynamic analysis and visualization of water vapor diffusion through building components. *ASHRAE Transactions*, Vol. 99, Pt.1, 288-296.

Mahdavi, A., and P. Mathew. 1992. *Hygro-thermal behavior of building components with regard to their impact on energy consumption and indoor climate*. CIB '92, World Building Congress, Montreal, Canada.

ÖNORM (1989): ÖNORM B 6015 Teil 2 (Vornorm): *Bestimmung der wärmeleitfähigkeit mit dem plattengerät; weiterbehandlung der mebwerte für die anwendung im bauwesen* (Determination of the thermal conductivity by the guarded hot plate apparatus; Treatment of the measured values for the application in building engineering). Austrian Institute for Standardization.

Panzhauser, E., A. Fail, A. Mahdavi, and W. Heindl. 1990. *Characteristic values for thermal behavior of building components compared with respect to their practical usability*. International CIB W67 Symposium on Energy, Moisture and Climate in Buildings, Rotterdam.

Sigmund, A. 1984. *Fenchtigkeit in bauwesen (Moisture in building) in Grundzüge der bauphysik (Fundamentals of building physics)*. Wien-New York: Springer-Verlag, 217-286.

Standaert, P. 1988. *GLASTA: Computer program to calculate vapor transfer -condensation - drying us-*

ing an extended method of Glaser. Building Physics Research Software Advice, Maldegem, Belgium.

Wiese, G. 1985. Wasserdampfdiffusion: Ein beitrag zur praktischen bauphysik (Water vapor diffusion: a contribution towards practical building physics). *Teubner Studienskripten*, Stuttgart, Germany.

A Simple Algorithm for Determining the Thermal Resistance of a Wall

Elisabeth Kossecka, Jan Kosny, and Jeffrey E. Christian

ABSTRACT

This paper presents a simple mathematical method of estimating wall thermal resistance based on measurements of the wall surface temperature and heat flux. The article analyzes integral formulae for the heat flow in finite time across a wall surface at prescribed surface temperatures, with the terms related to heat capacity separated. The solution makes it possible to minimize the wall measurement period necessary to estimate the wall current time material thermal resistance for time intervals with close-to-zero thermal flux. This method does not detect dynamic changes in thermal properties such as those caused by thermal drift or moisture adsorption / desorption. The algorithm was examined during field tests of foundation wall systems conducted at Oak Ridge National Laboratory.

Elisabeth Kossecka is a professor at the Institute of Fundamental Technological Research of the Polish Academy of Sciences in Warsaw, Poland, conducting research in thermal processes in building envelopes.

Jan Kosny is an adjunct professor in the Building Department at the Rzeszow University of Technology, Rzeszow, Poland. He is on leave at Oak Ridge National Laboratory in Oak Ridge, Tenn.

Jeffrey E. Christian is a researcher at the Oak Ridge National Laboratory in Oak Ridge, Tenn., currently conducting research in building, roof, wall, and foundation systems.

INTRODUCTION

The thermal efficiency of passive solar systems has been studied by J. Kosny, E. Kossecka, and their colleagues as part of the Polish Program of Energy Conservation in Buildings (Kosny, Starakiewicz, and Szymanski 1986-90) (Kossecka et al. 1989). As part of that work, they have studied theoretically the problem of heat exchange between a building wall or separated envelope element and its surroundings during long time intervals. This paper discusses an experimental application of a proposed mathematical solution for the homogeneous massive wall (Kosny 1990) (Kossecka 1991) (Kossecka 1992) as a calculation method increasing the accuracy of R-value estimations based on experimental results for short measure periods with the fluctuating, close-to-zero thermal flux. The accuracy of wall R-value estimation during periodic changes in exterior temperatures was also discussed by Flanders and Mack (1991). The foundation walls performance investigation conducted at Oak Ridge National Laboratory (ORNL) by Jeff Christian helped verify the accuracy of this mathematical method (Christian 1991) (Christian and Hameister 1993 draft).

HEAT FLOW ACROSS THE WALL

Consider a plane wall of thickness L, in which the one-dimensional heat transfer condition is satisfied. Let Fourier's law and the one-dimensional heat equation be satisfied (Carslaw and Jaeger 1959).

$$q = -k\,\frac{\partial T}{\partial x} \qquad (1)$$

$$\rho\, c\, \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k\, \frac{\partial T}{\partial x} \right] \tag{2}$$

The thermophysical properties of the wall—thermal conductivity k, specific heat c, and density ρ—are constant in time. The temperature in the wall is represented by the function $T(x,t)$ of the spatial coordinate x and the time t. The heat flux is also represented by the function $q(x,t)$.

In the case of a multilayer wall composed of materials of different thermal properties, Equation (2) has to be understood symbolically as a set of heat conduction equations written for the separate layers and the equations of continuity of temperatures and heat flow rates at the interfaces. The following equations assume a coordinate system in which wall surfaces correspond to the planes x = 0 and x = L (**Figure 1**). The boundary values of temperatures and heat fluxes are denoted by $T(0)$, $T(L)$, $q(0)$, and $q(L)$ respectively; the fluxes in the direction perpendicular to the wall surfaces are denoted by $q_n(0)$ and $q_n(L)$. In the assumed coordinate system:

$$q_n(0) = -q(0)$$

and

$$q_n(L) = q(L) \tag{3}$$

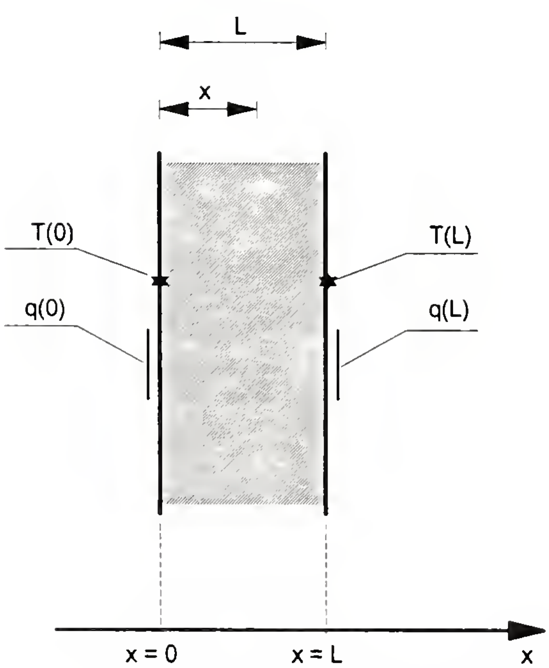


Figure 1. Experimental wall schematic.

Let $R_{0\text{-}x}$ and $R_{x\text{-}L}$ denote the heat resistances of the wall layers enclosed in the intervals $(0, x)$ and (x, L) respectively:

$$R_{0-x} = \int_0^x \frac{dx'}{k(x')},$$

and

$$R_{x-L} = \int_x^L \frac{dx'}{k(x')} \tag{4}$$

The total heat resistance is denoted by R. $R_{0\text{-}x}$, $R_{x\text{-}L}$, and R satisfy the following identity:

$$\frac{R_{0-x}}{R} + \frac{R_{x-L}}{R} \equiv 1 \tag{5}$$

After multiplying the conduction equation (Equation 2) for temperature $T(x,t)$ by $R_{x\text{-}L}/R$ and integrating by parts, from 0 to L, the expressions appearing on its right and left sides, we can obtain the following equality:

$$\int_0^L dx \left(\frac{R_{x-L}}{R}\right) \rho c\, \frac{\partial T}{\partial t} = \int_0^L dx \left(\frac{R_{x-L}}{R}\right) \frac{\partial}{\partial x}\left[k\, \frac{\partial T}{\partial x}\right]$$

$$= \left(\frac{R_{x-L}}{R}\right) k\, \frac{\partial T}{\partial x}\Big|_{x=0}^{x=L} + \frac{1}{R}\int_0^L dx\, \frac{\partial T}{\partial x} =$$

$$q(0) + \frac{1}{R}\left[T(L) - T(0)\right] \tag{6}$$

The analogous equations in which $q(L)$ appears are to be obtained by multiplying (Equation 2) by $R_{0\text{-}x}/R$:

$$q_n(0) = -\frac{1}{R}\left[T(0) - T(L)\right] - \int_0^L dx\, \frac{R_{x-L}}{R}\, \rho c\, \frac{\partial T}{\partial t} \tag{7}$$

and

$$q_n(L) = -\frac{1}{R}\left[T(L) - T(0)\right] - \int_0^L dx\, \frac{R_{0-x}}{R}\, \rho c\, \frac{\partial T}{\partial t} \tag{8}$$

Assuming now the constant-in-time thermophysical properties of the wall and integrating

overtime (Equations 7 and 8), we obtain the following integral formulae for the total amount of heat flow across the surfaces of the wall:

$$Q_n(0, t_0, t) = -\frac{1}{R}\int_{t_0}^{t} dt' \, [T(0) - T(L)] - \int_0^L dx \, \frac{R_{x-L}}{R} \, \rho c[T(x, t) - T(x, t_0)] \qquad (9)$$

and

$$Q_n(L, t_0, t) = -\frac{1}{R}\int_{t_0}^{t} dt' \, [T(L) - T(0)] - \int_0^L dx \, \frac{R_{0-x}}{R} \, \rho c[T(x, t) - T(x, t_0)] \qquad (10)$$

Summing up both sides of Equations (9) and (10) and taking into account identity (Equation 5), we can write the heat balance of the wall in the following form:

$$Q_n(0) + Q_n(L) = - Q_c \qquad (11)$$

where Q_c denotes the difference of the amount of heat stored in the wall:

$$Q_c(t_0, t) = \int_0^L dx \, \rho c \, [T(x, t) - T(x, t_0)] \qquad (12)$$

Let Q_{c0}, and Q_{cL} denote the following quantities:

$$Q_{c0} = \int_0^L dx \, \frac{R_{x-L}}{R} \, \rho c \, [T(x, t) - T(x, t_0)] \qquad (13)$$

and

$$Q_{cL} = \int_0^L dx \, \frac{R_{0-x}}{R} \, \rho c \, [T(x, t) - T(x, t_0)] \qquad (14)$$

Q_{c0} and Q_{cL} may be interpreted as the components of the total heat flow across the wall surfaces contributing to the difference in the amount of heat stored in its volume of unit cross-section. Under the assumptions made previously about the time independence of the physical parameters of materials, the quantities Q_{c0} and Q_{cL} depend exclusively on the temperature differences in the initial and final states; if there is no temperature difference, the Q_{c0} and Q_{cL} vanish. For prescribed temperatures of the wall surfaces $T(0)$ and $T(L)$, they are the only unknown components of the heat flows $Q_n(0)$ and $Q_n(L)$ across those surfaces. If there is no temperature difference between the surfaces (symmetric heating or cooling), Q_{c0} and Q_{cL} are almost equivalent to $Q_n(0)$ and $Q_n(L)$.

Denoting by $\overline{T}$, $\overline{T}(L)$, $\overline{q}(0)$, and $\overline{q}(L)$ the boundary temperatures and heat fluxes averaged over the time interval of the length Δt, the formulae (9) and (10) may be rewritten as the following:

$$\overline{q_n}(0) = -\frac{\overline{T}(0) - \overline{T}(L)}{R} - \frac{Q_{c0}}{\Delta t} \qquad (15)$$

and

$$\overline{q_n}(L) = -\frac{\overline{T}(L) - \overline{T}(0)}{R} - \frac{Q_{cL}}{\Delta t} \qquad (16)$$

Expressions (15) and (16) can be solved with respect to $1/R$, which gives the following dependence:

$$\frac{1}{R} = \frac{\overline{q_n}(0)}{\overline{T}(L) - \overline{T}(0)}[1 + \gamma_n(0)] = \frac{\overline{q_n}(L)}{\overline{T}(0) - \overline{T}(L)}[1 + \gamma_n(L)] \qquad (17)$$

where:

$$\gamma_n(0) = \frac{1}{\overline{q_n}(0)} \frac{Q_{c0}}{\Delta t} \qquad (18)$$

and

$$\gamma_n(L) = \frac{1}{\overline{q_n}(L)} \frac{Q_{cL}}{\Delta t} \qquad (19)$$

HOMOGENOUS WALL AND ASYMPTOTICALLY STEADY HEAT FLOW

An examination of Equations (13) and (14) indicates that the component of Q_c corresponding to a given surface is generally more sensitive to the temperature difference in the vicinity of this surface than in the vicinity of the opposite one. However, there are additional factors—the thermal capacity and resistance distribution. In general, evaluation of the quantities Q_{c0} and Q_{cL}, contributing to the difference in the amount of heat stored in the wall Q_c, for prescribed temperatures $T(0,t)$ and $T(L,t)$, makes it necessary to solve the transient heat conduction problem. Explicit expressions can be written for the heat conduction process, for which the initial and final temperature distribution in the wall correspond (in the sense of asymptotical convergence) to the steady state heat flow. They can be written as follows:

$$T(x) = \frac{x}{L} T(L) + \frac{L - x}{L} T(0) , \tag{20}$$

$$\frac{R_{0\text{-}x}}{R} = \frac{x}{L} , \tag{21}$$

and

$$\frac{R_{x\text{-}L}}{R} = \frac{L-x}{L} \tag{22}$$

The amount of heat accumulated by the wall may be expressed in the following forms which are derived by integration Equations (12), (13), and (14):

$$Q_{c0} = L\rho c \frac{1}{2}\left[\frac{2}{3}\Delta T(0) + \frac{1}{3}\Delta T(L)\right] \tag{23}$$

and

$$Q_{cL} = L\rho c \frac{1}{2}\left[\frac{1}{3}\Delta T(0) + \frac{2}{3}\Delta T(L)\right] \tag{24}$$

and

$$Q_c = L\rho c \frac{1}{2} [\, \Delta T(0) + \Delta T(L)] , \tag{25}$$

where

$$\Delta T(0) = T(0, t) - T(0, t_0) , \tag{26}$$

and

$$\Delta T(L) = T(L, t) - T(L, t_0) \tag{27}$$

Q_{c0} is twice as sensitive to the variation of T(0) as to the variation of $T(L)$; the opposite holds for Q_{cL}. Equations (23) and (24) may be helpful in estimating the magnitude of the terms $Q_{c0}/\Delta t$ and $Q_{cL}/\Delta t$ in expressions (15) and (16) for $q_n(0)$ and $q_n(L)$ and the magnitude of the ratios $\gamma_n(0)$ and γ_n(L) defined by (18) and (19). This can help in determining wall R-value by using formula (17). When the performance of the massive storage wall with very light or transparent insulation is examined, $Q_{c0}/\Delta t$ and $Q_{cL}/\Delta t$ values may be inspected through temperature measurements with the help of sensors located on the interior and exterior surfaces of the wall, and inside the wall (Kosny 1990).

EXPERIMENTAL APPLICATION

Expression (17) may serve as an algorithm for determining the thermal resistance of the wall on the basis of measurements of surface heat fluxes and temperature. For steady inside surface temperature $\Delta T(L, t_0, t) = 0$, $\gamma_n(L, \gamma t)$ can be described by the following dependence:

$$\gamma_n(L, \Delta t) = \frac{\dfrac{(\Delta T(0)}{\Delta t}}{\dfrac{6k}{L^2\rho c}[\bar{T}(0) - \bar{T}(L)] - \dfrac{\Delta T(0)}{\Delta t}} \tag{28}$$

where wall material thermal conductivity is denoted by k.

Let A, B, C denote the following quantities:

$$A = \frac{\Delta T(0)}{\Delta t} ,$$

$$B = \bar{T}(0) - \bar{T}(L) ,$$

$$C = \frac{6k}{L^2 \rho c} \qquad (29)$$

Then formula (28) may be rewritten as below:

$$\gamma_n (L, \Delta t) = \frac{A}{CB - A} \qquad (30)$$

In light of the fact that for long-time measurements the terms $Q_{c0}/\Delta t$ and $Q_{cL}/\Delta t$ often may be neglected, values $\gamma_n(0)$ and $\gamma_n(L)$ are very small compared with unity. That is why approximate wall thermal resistance R^o, in case of simple averaging calculations, can be estimated from the following expression:

$$\frac{1}{R^o} \approx \frac{\overline{q}_n (0)}{\overline{T} (L) - \overline{T} (0)} \approx \frac{\overline{q}_n (L)}{\overline{T} (0) - \overline{T} (L)} \qquad (31)$$

If Equations (16) and (31) are compared, the following dependence can be obtained:

$$\frac{R^o}{R} = 1 + \gamma_n (L, \Delta t) \qquad (32)$$

Equation (31) is commonly used to estimate approximate wall R-values based on surface thermal flux and temperature measurements. According to Equation (32), the error of such estimation is as small as the $\gamma_n(L)$ value which is close to zero. That is why a knowledge of the $\gamma_n(L)$ value (referred to hereafter as a correction ratio) may help to estimate an accuracy of, based on Equation (30), approximate R-value calculations. In **Figure 2**, values of the correction ratio are shown for several solid concrete walls, 12, 8, and 4 inches thick, made of 120 lb/ft^3 and 40 lb/ft^3 concretes. It can be seen that for surface temperature differences $T(0)$-$T(L)$ equal 50°F, a value of $\gamma_n(L)$ can be smaller than

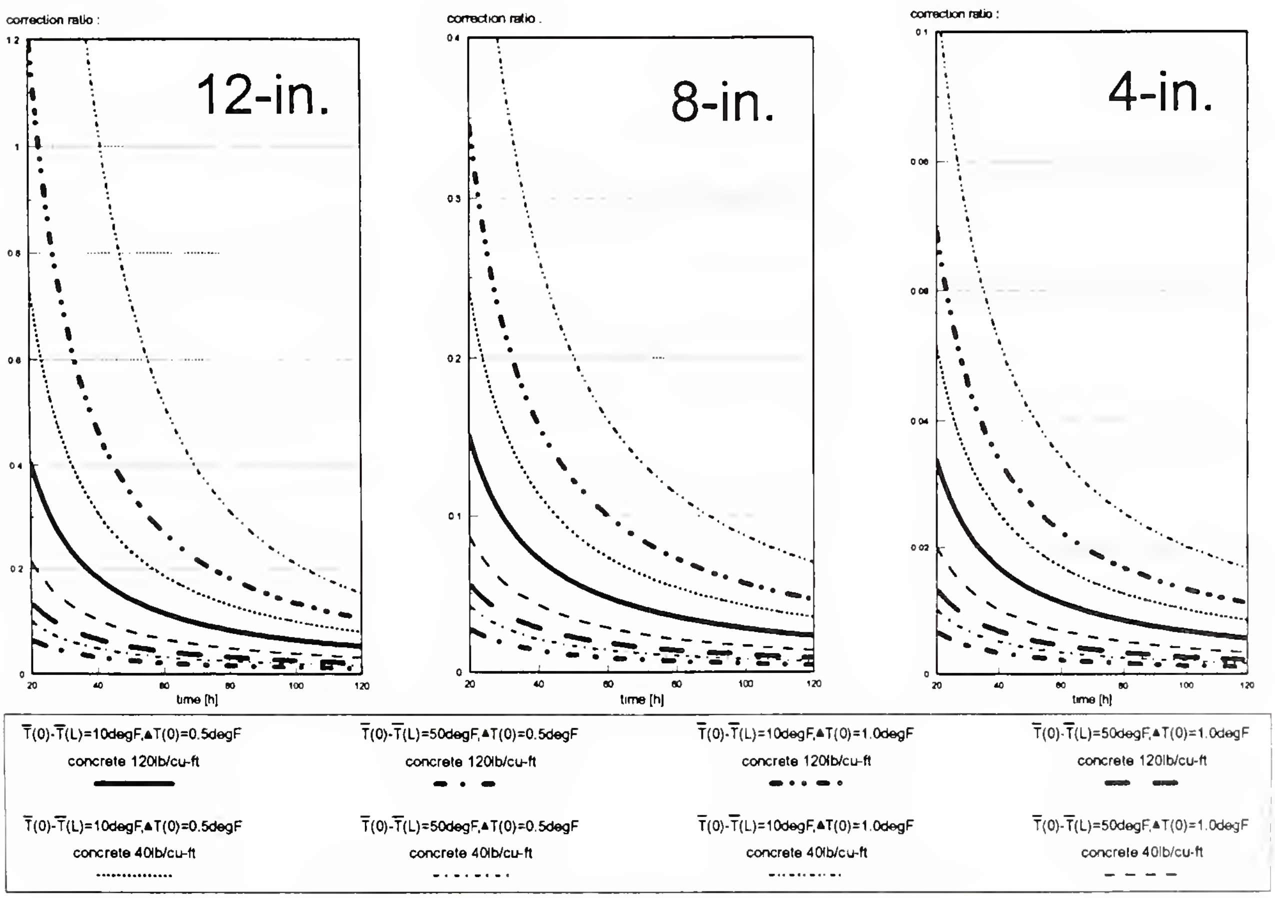


Figure 2. Correction ratios for solid concrete walls.

0.05 for 4-day measure periods in case of 12-inch walls and for 2-day periods for 8-inch walls. In case of 4-inch walls, a value of $\gamma_n(L)$ can be smaller than 0.01 for 2-day measure periods, and for the same $T(0)$-$T(L)$, surface temperature differences. A reason for achieving such small values of $\gamma_n(L)$ lies in the fact that vary small values of differences were assumed between initial and final wall surface temperatures, $T(0)$.

In practice, based on temperature profile observations, it is possible to select time periods where the differences between initial and final temperatures, $\Delta T(0)$, are minimal, and thermal flux does not change in direction of flow. **Figure 3** presents values of temperature differences $\Delta T(0)$ that can lead to estimation R-values with an error of less than 5 percent (correction ratio values γ_n are less than 0.05).

Based on the ORNL foundation wall experimental results (Christian and Hameister 1993 draft), the authors selected, for an uninsulated wall, measurement periods where the initial and final states of the wall were almost equal to minimize $\Delta T(0)$. Then R-values were calculated. By selecting time intervals during which the initial and final temperatures of the wall surface where the thermal flux meter was located, were almost equal, it was possible to estimate R-values even for 2-day measurement periods (**Figure 4**). Results were compared with R-values obtained by use of the PROPOR computer code (Beck, Petrie, and Courville 1991) and with R-values calculated according to Equation (31), both for 7-day time intervals. These are shown in **Figure 5**. Most of the results for the spring and fall months are in good agreement. For summer, because of very small and fluctuating thermal flux, calculated wall R-values are divergent. It was possible, by selecting time intervals, to obtain relatively accurate wall R-values even for 2-day measurement periods (too short for the traditional, averaging way of R-value computations, and for PROPOR analyses). For selected time periods, it was also possible to estimate wall R-values for considerably smaller values of average thermal flux. **Table 1** presents calculated wall R-values for June 1991 obtained by using the PROPOR computer code and Equation (31) for selected shorter periods.

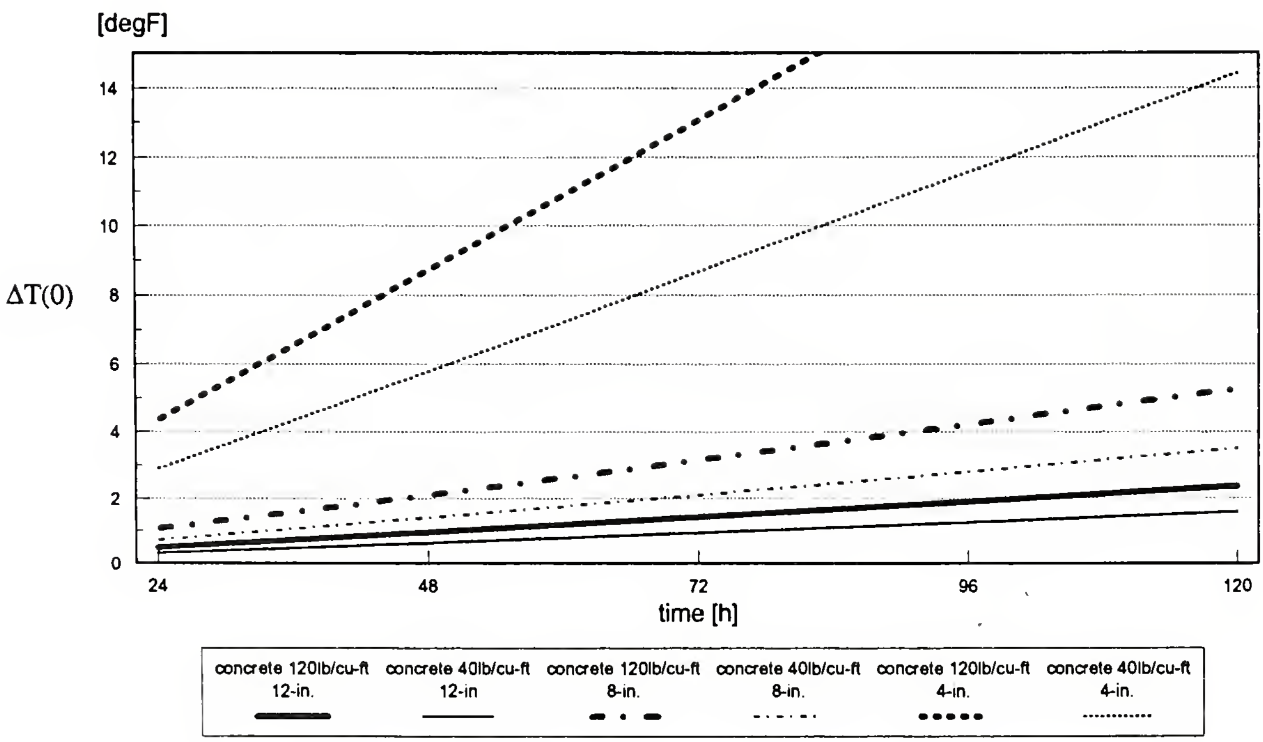


Figure 3. Maximum values of ΔT(0) for concrete solid walls giving correction ratios less than 0.05.

CONCLUSIONS

From the analysis of the formulas (9), (10), (15), (16), (17), (18), and (20), a series of conclusions may be developed that can be useful in experimental analyses of wall thermal properties. Some of them are as follows:

- The heat flow through the wall is the same for all heat transfer processes with the same initial and final surface temperatures, and thermal flux not changing in direction of flow.
- Over long time intervals, the mass distribution inside the wall has no influence on the heat flow under cyclical surface temperatures.
- When the thermal resistance of the wall is to be determined on the basis of surface temperatures and heat flux measurements, with the use of approximate formula (19), the error can be minimized if the experiment is conducted so that the initial and final temperatures at the point of the thermal flux measurement are close. This can shorten

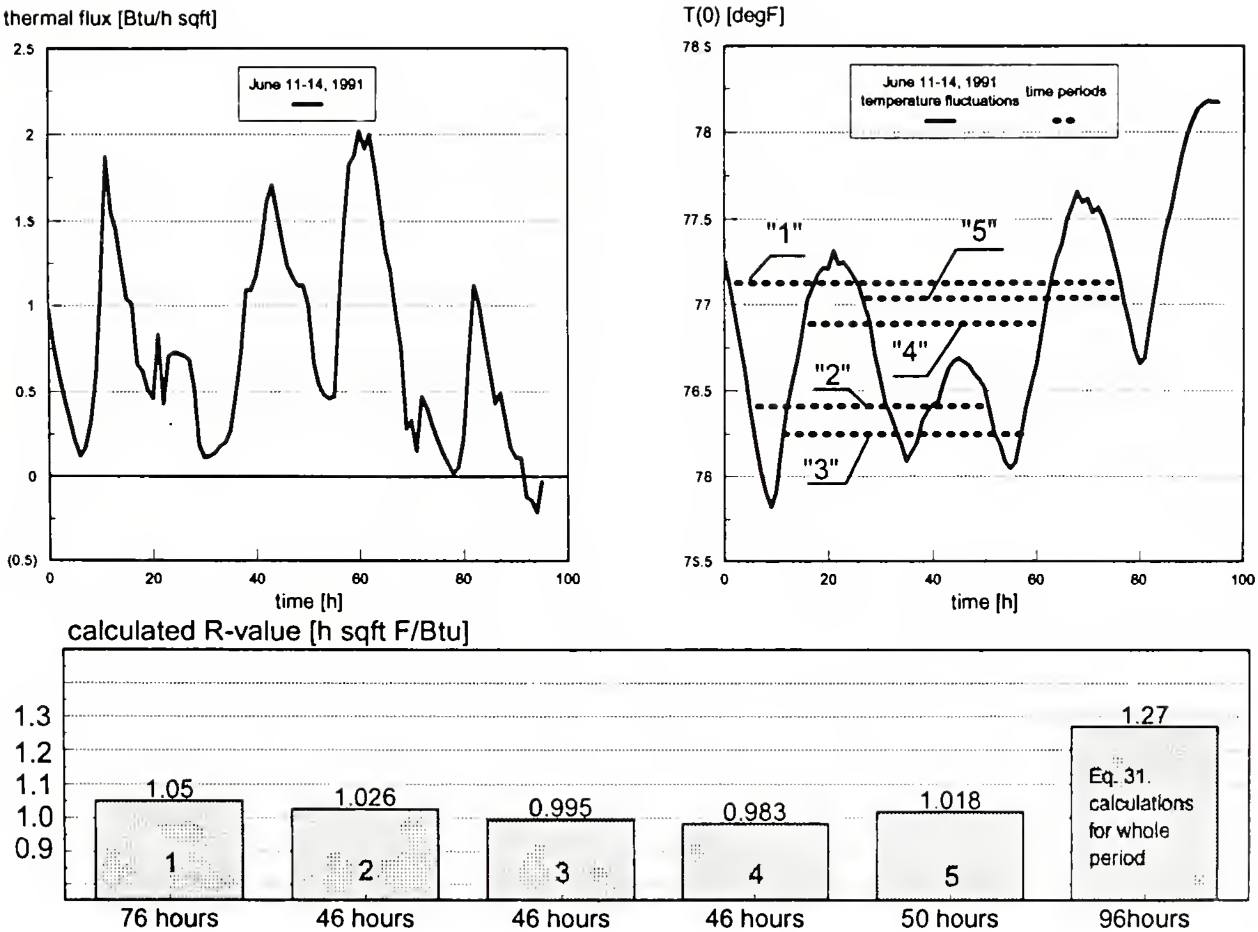


Figure 4. R-value calculations for periods selected by thermal flux and temperature profile observations.

measurement periods, which aids the experimental estimation of wall thermal properties for time intervals with small and fluctuating thermal flux.

- The integral formulae (9) and (10) describe the total amount of flow across the surfaces of the wall. They can be used in analyzing the influence of variations of the temperature profile inside the wall on the heat flow across its surfaces for a given wall resistance and thermal capacity distribution.
- The correction factor γ_n, describing inaccuracy of R-value estimation by approximate Equation(31), may be predicted by use of roughly estimated wall parameters and the formulae for the steady state heat flow.

Some of the above conclusions are intuitively obvious or well known; however, it is worthy to note that this paper presents a strict mathematical basis for them in the form of the integral formulae for heat flow across wall surfaces.

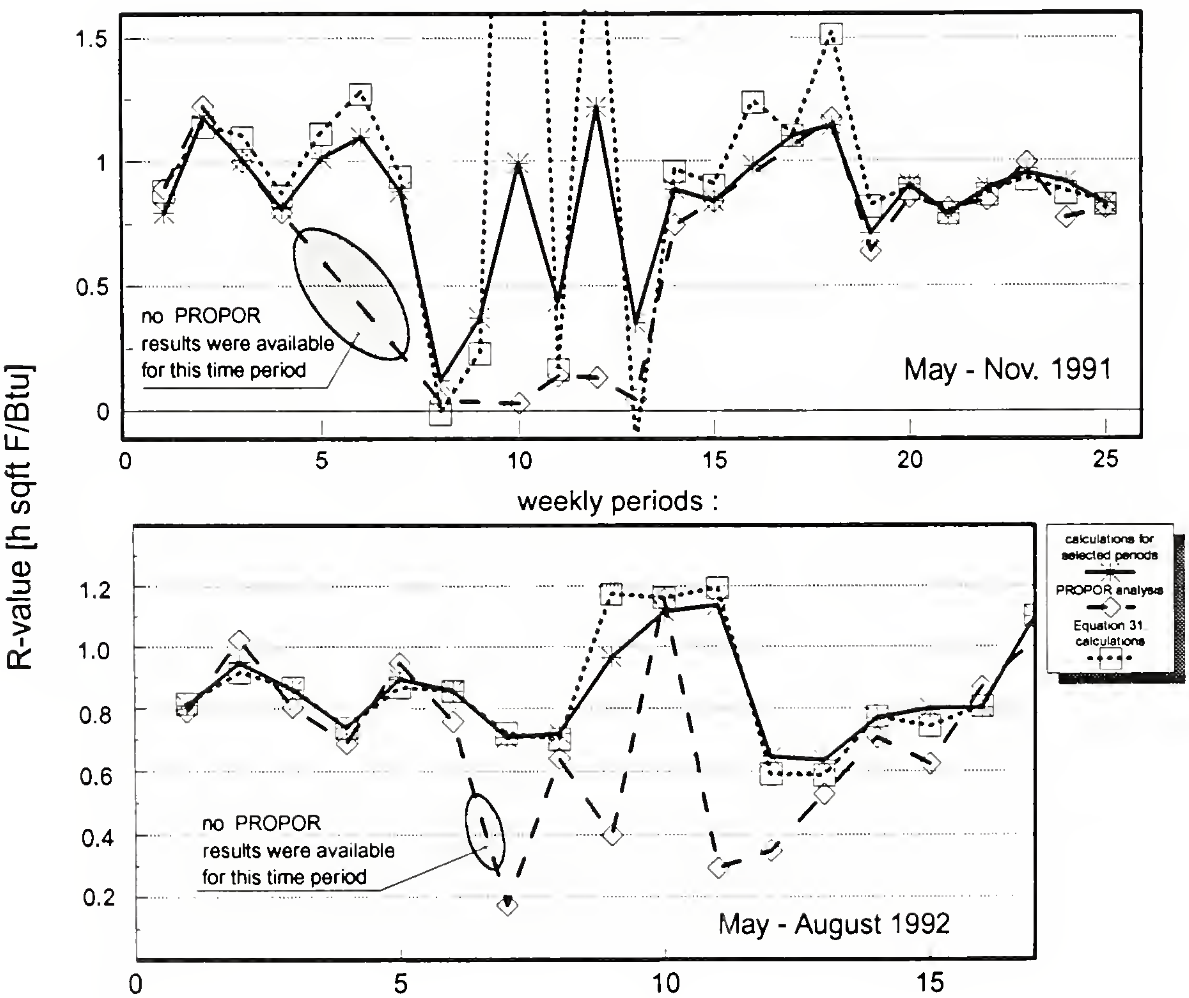


Figure 5. Experimental R-values for several calculation methods.

Table 1. Comparison of calculated R-values

Testing interval	Length of interval (h)	Average thermal flux [Btu(h·ft^2)$^{-1}$]	Calculated R-values [h·ft^2·F/Btu] Using PROPOR	Calculated R-values [h·ft^2·F/Btu] Using Eq. 31
Period beginning June 3, 1991				
Entire period	96	1.029375	0.795548	0.862072
Hours 51-96	45	1.332706		0.830663
Hours 35-87	52	1.427924		0.789244
Period beginning June 11, 1991				
Entire period	96	0.738645		1.109011
Hours 1-76	75	0.855394		1.033225
Hours 14-60	46	0.855744		0.992541
Period beginning June 17, 1991				
Entire period	144	0.382013		1.271223
Hours 2-54	52	0.523018		1.096681
Hours 18-61	43	0.495454		1.171559
Period beginning June 24, 1991				
Entire period	168	0.812321		0.936689
Hours 16-116	100	1.026039		0.861237
Hours 5-122	117	0.948389		0.877580

REFERENCES

Beck, J.V., T.W. Petrie, and G.E. Courville. 1991. Using parameter estimation to analyze building envelope thermal performance. *In-situ heat flux measurements in buildings*. U.S. Army Cold Regions Research and Engineering Laboratory. Special report, February.

Carslaw, H.S. and J.C. Jeager. 1959. *Conduction of heat in solids*. Oxford: Oxford University Press.

Christian, J.E. 1991. *An HFT guard plate for exterior envelope surface measurements*. In-situ heat flux measurements in buildings. U.S.Army Cold Regions Research and Engineering Laboratory. Special report, February.

Christian, J.E. and J. Hameister. 1993 draft. *Basement insulation energy savings*. To be published as an Oak Ridge National Laboratory report.

Flanders, S.N. and R.T. Mack. 1991. Prediction of errors for in-situ measurement of thermal resistance. *In-situ heat flux measurements in buildings*. U.S. Army Cold Regions Research and Engineering Laboratory. Special report, February.

Kosny, J., A. Starakiewicz, and W. Szymanski. 1986–1990. Investigation of storage solar walls and air collectors efficiency. *CPBP* 02.21.2.5. reports I–V. Rzeszow, Poland (in Polish).

Kosny, J. 1990. *Theoretical and experimental analysis of solar storage wall efficiency*. (Ph.D. thesis.) IPPT PAN, Polish Academy of Sciences. Warsaw, Poland (in Polish).

Kossecka, E. 1991. Heat balance of simple solar heating systems and building walls within long time intervals. *Archives of Civil Engineering*, 37(2), 249-64. Warsaw, Poland (in Polish).

Kossecka, E.1992. Heat transfer through building wall elements of complex structure. *Archives of Civil Engineering*, 38(1–2), 117–26. Warsaw, Poland.

Kossecka, E., J. Kosny, Z. Pretczynski, and A. Starakiewicz. 1989. *Study of storage solar walls*. Second Conference on Building Science. Lodz, Poland (in Polish).

News, Updates, and Seminars...

Geosynthetics in Residential Construction

John S. Horvath, Ph.D., P.E.
Associate Professor of Civil Engineering
Manhattan College
Bronx, New York

The civil engineering profession is starting to take greater interest in applying geosynthetics technology to residential and light commercial/industrial structures. The general neglect of this market to date is based primarily on the educational emphasis to which all civil engineers are exposed. By omission from course material, civil engineers develop the perspective that residential and similar construction does not require engineering attention. As the readers of the Building Research Journal are well aware, this is a fallacy that needs correction. The purpose of this article is to offer an overview of some developments that the writer is familiar with that have particular application in residential and related construction. It is hoped that this will initiate a discussion among the diverse interests who are involved in this construction area.

A concept that is currently in the early stages of development is that of a "geosynthetic envelope" around the below-ground portion of the structure. Among the various geosynthetic products that are available, the two that are the basic elements in this concept are geofoams and drainage geocomposites. The concept is to place layers of these two materials around the entire below-ground portion of a structure with the drainage geocomposite being the outer layer that is in contact with the ground.

Geofoam is a new but accepted term for any foam product used in a below-ground application. Based on experience to date, the primary geofoam materials are the two types of rigid cellular polystyrene (RCPS): expanded polystyrene (EPS or "beadboard") and extruded polystyrene (XPS). Conventionally, RCPS is installed as panels typically in the range of 25mm to 75mm thick placed on the exterior of the below-ground walls and, in some cases, beneath the basement slab. However, there has been a rapid growth in systems where RCPS panels or hollow blocks are used as formwork for a poured-in-place concrete wall. One of the growing concerns with using RCPS in below-ground applications is damage caused by insect infestation. A relatively recent development is a passive treatment that is applied during manufacture. Research indicates that this treatment is successful in deterring insect infestation, at least for termites and carpenter ants. At the present time this treatment is available only in North America and only for EPS panels from certain manufacturers.

Traditionally, the geofoam layer is envisaged only as providing the function of thermal insulation to reduce life-cycle energy costs. In this regard it is worth noting that not only can thermal insulation reduce costs during the heating season but there is also a potential for reducing dehumidification costs, at least for below-ground space, during the summer. This is because the presence of thermal insulation moves the dew point from inside the below-ground space to outside. Electric-energy cost savings from reduced dehumidification should therefore be considered where appropriate. A new thermal insulation application in the U.S. is called the "frost-protected shallow foundation" (FPSF) concept. This applies to structures in relatively cold climates that do not have below-ground space. In these areas, the structure footings must be founded at significant depths, sometimes in excess of two meters, to be below the seasonal frost depth. This adds a significant cost to construction. By insulating the structure perimeter, footing embedment can be reduced to as little as 500mm. In addition, there will be life-cycle energy savings as well. This concept has been used in Europe and elsewhere for more than 30 years. Current U.S. activities involve some instrumented houses in the northern U.S. as well as efforts to incorporate provisions for such construction in the various model building codes in use throughout the U.S.

Some new, additional functions of geofoam are currently being investigated. This involves using the foam as a "compressible inclusion" to reduce earth pressures acting on below-ground walls, especially in situations involving seismic loading, swelling clays, and freezing soils. The potential benefit of these new applications is significant especially considering that the geofoam will still provide traditional value as thermal insulation. At the present time, research indicates that only panels of EPS can be manufactured to provide the necessary properties to act as a compressible inclusion. This is fortuitous in view of the fact that only EPS panels can be treated against insect infestation as noted above.

The use of a drainage geocomposite can also provide several benefits. In addition to the obvious one of intercepting ground water before it enters below-ground space, a drainage layer minimizes the water absorbed by the geofoam layer thereby maximizing its thermal efficiency. There is also a potential that the drainage layer can be used as part of a system to intercept ground-borne gases such as radon. The use of a geocomposite as the drainage material offers benefits over the use of natural aggregates (gravel or crushed rock) both in terms of cost in many areas as well as construction cost savings in ease of placement. There is even one drainage geocomposite that has a significant thermal-insulative value that can contribute in this area as well.

In summary, the use of a "geosynthetic envelope" around the below-ground portion of structures has great potential for providing simultaneous, multiple benefits in a cost-effective manner. I welcome contact and comments from those with similar research interests. I can be reached at:

Prof. John S. Horvath, P.E.
Associate Professor of Civil Engineering
Manhattan College
Civil Engineering Department
Bronx, New York 10471
Telephone: 718-920-0177
Fax: 718-796-9812

From Other Universities —

University of Illinois at Urbana-Champaign School of Architecture-Building Research Council (BRC)

The Council is developing its role as a national publisher of research- and application-oriented materials. Projects include publication of residential home-owner materials; translation of selected materials into Spanish, and a national solicitation of manuscripts appropriate to research, technology, and home-owner publication.

BRC research efforts include an agreement with State Farm to investigate the problem of burst water pipes resulting from subfreezing temperatures. CertainTeed will continue and expand its support of attic performance research. The project, "Design and Implementation of a Home Energy Rating System", includes information transfer to the home-building/sales industry; consumer education; home energy rater training and support; and informational data-basing.

Through seminars sponsored by the Illinois Attorney General's office, BRC provided technical information for the repair of flood-damaged houses to victims of the 1993 Mississippi flood. These seminars provided citizens with consumer protection information. Other participants included the Illinois chapter of NAHB and FEMA.

Due to staff cutbacks, increased research opportunities, and spiraling demands for public service during the 1993 summer flood, BRC was forced to suspend its housing advisory line service. Architects, contractors, and home owners in Illinois and across the nation have come to depend on this service to answer home construction, design, maintenance, and remodeling questions. Funds are being sought to hire a housing expert half-time to reinstate the line.

1994 is the Council's fiftieth anniversary and the Year of the Alumni. BRC encourages all who have worked with researchers at the Council to contact us by calling us at 800-336-0616, or by writing to us at BRC / 1 East St. Mary's Road/ Champaign, IL 61820. We would like to hear where you are and what you are doing, whether you would like a newsletter about Council and alumni activities, and how you

would like to renew ties to BRC and its missions.

University of Florida
Shimberg Center for Affordable Housing

The Shimberg Center organized the 4th Rinker International Conference on Building Construction with the theme of "Affordable Housing: Present and Future." As a result of this conference, the Center established an international network of over 100 housing and housing-related researchers and professionals in over 50 countries, plus a large number in the U.S. This network, in turn, led the Center to propose re-establishment of W63: Low-cost Housing, one of the Working Commissions of the Netherlands-based International Council for Building Research Studies and Documentation (CIB). The success of the conference and the subsequent national and international recognition was directly related to the support received by the Center from Fannie Mae's Office of Housing Research, the National Housing Endowment, and the Nations Bank.

University of Oregon
The Center for Housing Innovation (CHI)

CHI has undertaken the Energy Efficient Industrialized Housing Research Program (EEIH). This program, funded by the U.S. Department of Energy, private industry, state governments and utilities, addresses the need to increase the energy efficiency of industrialized housing through both design and production improvements. The Center's goal is to conduct research that will develop techiques to produce marketable industrialized housing that is 25 percent more energy efficient than the most stringent U.S. residential codes now require and will cost less.

University of Georgia
Housing Research Center

The Center completed work on "An Assessment of Changes in Energy Behavior: Revisited", funded by the Governor's Office of Energy Resources, and "An Analysis of Water Quality from Private Wells in Georgia: The Influences of Land Use, Enonomic and Demographic Factors and Strategies for Families at Risk", which was funded by the USDA Agricultural Research Service.

Texas A&M University
Center for Housing Research and
Urban Development

The Center completed two community resource centers in the colonias along the Texas-Mexico border. Centers in the Cameron Park colonia near Brownsville, and a colonia in Progreso, near Weslaco, Texas, were completed during December, 1993. Ribbon cutting ceremonies are being planned for the Laredo and El Paso areas and sites for the fifth and sixth centers are being investigated.

Colorado State University
Housing Research Center
Program in Computer-Integrated
Construction Management

The current focus areas in the Center and the Program include corporate and project management, computer-integrated design and construction planning, international construction management, stabilization and historic preservation, and indoor air quality.

The Center and the Program have been involved in the following initiatives and projects related to international construction management:

- Construction safety training for the Ministry of Labour, Cyprus;
- Computer-integrated planning and scheduling training for officials from Pakistan;
- Provision of environmental technical assistance as part of a team effort to Ex-Soviet Union countries;
- A visit by the former president of the School of Planning and Architecture, New Delhi, India, to explore the possibilities of mutual cooperation. (The School has graduate programs in Building Engineering and Management and Housing Planning Development.)
- A seminar presentation on "Computer-Integrated Design and Construction" at the School of Planning and Architecture, New Delhi, India.

ORDER FORM

ne ______________________________

eet Address ______________________________

y ______________ State __________ Zip __________

ne (______) __________ Fax (______) __________

SEND ORDERS TO:
School of Architecture–Building Research Council
College of Fine and Applied Arts
University of Illinois at Urbana-Champaign
One East St. Mary's Road
Champaign, IL 61820

CALL: (800) 336-0616 FAX: (217) 244-2204

	DOMESTIC	INT'L
❑ One year personal subscription to the *Building Research Journal*	$30.00	$36.00
❑ One year institutional subscription to the *Building Research Journal*	$80.00	$96.00

❑ VISA ❑ MasterCard

Acct #: ________-________-________-________

Exp. Date: ______________________________

Cardholder's Signature: ______________________________

ce your check or money order payable to the University of Illinois. On purchase orders, use your Federal Employers Identification nber.

ORDER FORM

ne ______________________________

eet Address ______________________________

y ______________ State __________ Zip __________

ne (______) __________ Fax (______) __________

SEND ORDERS TO:
School of Architecture–Building Research Council
College of Fine and Applied Arts
University of Illinois at Urbana-Champaign
One East St. Mary's Road
Champaign, IL 61820

CALL: (800) 336-0616 FAX: (217) 244-2204

	DOMESTIC	INT'L
❑ One year personal subscription to the *Building Research Journal*	$30.00	$36.00
❑ One year institutional subscription to the *Building Research Journal*	$80.00	$96.00

❑ VISA ❑ MasterCard

Acct #: ________-________-________-________

Exp. Date: ______________________________

Cardholder's Signature: ______________________________

ce your check or money order payable to the University of Illinois. On purchase orders, use your Federal Employers Identification nber.

The *Building Research Journal* serves building-related disciplines, including architecture, engineering, building science, materials research, construction, preservation, and real property management. The *Journal* is a forum through which the building research community is encouraged to address the broad issues of building technology and the specific challenges of building construction.

The *Journal* staff and editorial board welcome articles related to all aspects of building design, construction, government and social policy, operation, preservation, and performance. Articles accepted by the *Journal* meet the highest standards of scholarship, research, and technical merit. For a copy of the *Building Research Journal* Author Guidelines or to order the *Journal* contact the publisher:

School of Architecture-Building Research Council
College of Fine and Applied Arts
University of Illinois
One East St. Mary's Road
Champaign, Illinois 61820

Telephone: (217) 333-1801
Facsimile: (217) 244-2204

ISSN 92-002353